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EVALUATION OF CALCIUM LEVELS AND RATIOS
FOR OPTIMUM PLANT GROWTH IN THE SOIL
SOLUTION OF SOLONETZIC SOILS

BY



MARTIN ROGER CARTER

A THESIS

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Evaluation of calcium levels and ratios for optimum plant growth in the soil solution of Solonetzic soils" submitted by Martin Roger Carter in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This study was undertaken with the objective of determining if calcium is limiting for optimum plant growth on Solonetzic soils; and to establish useful parameters for assessing the calcium status of the soil solution. There were three main phases to the work as follows: displacement of the soil solution at field moisture levels; simulation of the displaced soil solution, by use of solution culture, so that, the physiological effect of the concentrations and ratios of ions on plant growth could be assessed free of any soil physical effects; and soil studies to determine if results from solution culture were an accurate assessment of plant growth in the soil.

Analysis of displaced soil solutions at half available moisture percentage ($-1/3 + -15\text{bar}/2$) indicated that a significant decrease in salinity and magnesium to calcium ratio (Mg/Ca) and increase in calcium to total cation ratio (Ca/TC) occurred along the Solonetz to Solod soil sequence. A decrease in soil moisture from saturation paste to half available moisture percentage gave an increase in salinity and slight increase in the Mg/Ca ratio. High Mg/Ca ratios (1.16 - 3.57) and low Ca/TC ratios (0.04 - 0.07) were found in the soil solution of the Ap horizons of Solonetz; and

Bnt horizons of Solonetz and Solodized Solonetz soils used in the study.

Yields and root growth of barley (Hordeum vulgare var Galt), in solution culture, were reduced when the Mg/Ca ratio in solution exceeded 1.0, or when the Ca/TC ratio was lower than 0.15; regardless of levels of salinity, concentrations of calcium or magnesium, or differences in ionic strength. The Ca/TC ratio was found to be more versatile than the Mg/Ca ratio. These results agree with research on other plant species. Reduced growth was followed by symptoms of calcium deficiency such as withering of the emerging leaf. Uptake of calcium was correlated ($r = 0.931$) with the Ca/TC ratio in solution, while the Mg/Ca uptake ratio was correlated ($r = 0.979$) with the Mg/Ca ratio in solution. The Ca/TC ratio in solution and not the potassium concentration was considered important in maintaining the ability of potassium to compete with sodium uptake and prevent potassium deficiency.

Growth of barley in soil from various horizons of Solonetzic soils verified the results found in solution culture, in that, soils shown by displacement to have adverse ratios of calcium to other ions, soon developed stunted growth and calcium deficiency. Additions of calcium, mixed into the soil, gave increases in growth, prevented calcium deficiency and improved calcium and potassium uptake.

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INTRODUCTION

Adverse factors affecting plant growth on Solonetzic soils are usually attributed to physical impediments which prevent root growth, disrupt the mobility of water and cause poor aeration of the soil. At the same time, physiological effects, such as salinity, low nitrogen, and ion concentrations and ratios have also been accredited some responsibility for reducing plant growth. Investigations into these latter effects have usually concentrated on the role of high exchangeable sodium (Pearson 1960), and general problems associated with salinity (Bernstein 1975).

Nutritional disturbances on Solonetzic soils, although mentioned in early reviews of the literature (Magistad 1945) and those more recent (Bernstein 1975) have not been adequately researched. For instance, calcium limitations for plant growth have often been considered important (Abraham and Szabolcs 1964; Abrol 1968; Bower and Turk 1946; Bronson and Fireman 1960; Kelly 1963; Pearson 1960; Poonia and Bhumbra 1973a; Ratner 1938; and Russell 1970). However, inconclusive results such as calcium ammendments increasing the calcium content of plants but not affecting

yield (Szabolcs et al. 1957), or increased yield corresponding to calcium loss from the soil (Cairns 1970) have prevented useful parameters, concerning calcium availability, being established.

A more recent approach to assess physiological effects on plant growth has been to estimate the concentrations and ratios of ions in the soil solution over field moisture ranges (Adams 1971a). This is based on the theory that the soil solution fully characterizes the environment of the plant root (Brewster and Tinker 1970; Lagerwerff 1958, 1960; and Olsen and Peech 1960). Determination of concentrations and ratios of ions at field moisture levels is significant for Solonchic soils due to the semi-arid climate in which these soils are found. Khan and Webster (1966) found that concentrations and ratios of ions varied more markedly over the moisture range of a Black Solonchic soil than that of an associated productive Eluviated Black Chernozemic soil. Therefore changes and differences in ion ratios may be important parameters by which to assess nutritional factors in Solonchic soils.

Recent research in other areas of agronomy have shown that a certain percentage of calcium must be present in the root environment to maintain optimum plant production (Adams 1971a; Epstein 1972; Geraldson 1971; Khasawneh 1971; and Pearson 1971). Further to this, levels of calcium

which are adequate under nonsaline conditions become limiting as salinity is increased (Bernstein 1975; LaHaye and Epstein 1969). As the effect of ion ratios are mainly important at the two extremes of nutrient supply, that is toxicity and deficiency, the determination of critical ratios of calcium to other ions could provide information concerning calcium availability.

Therefore, with the foregoing facts in mind, the objective of this study is to determine if calcium is limiting for optimum plant growth on Solonetzic soils; and to resolve if the relatively saline conditions found in some Solonetzic soils enhance the need for additional calcium. Attention will be given to determining useful parameters for calcium availability. To achieve this objective the study will be divided into four parts as follows:

- (1) Characterization of bulk samples from A and B horizons of several Solonetzic soils.
- (2) Determination of ion concentrations and ratios of calcium to other ions in the soil solution of Solonetzic soils under study, over the field moisture range.
- (3) Simulation of the ranges in sodium, calcium and magnesium concentrations and ratios as well as salin-

ity found in the soil solutions, by use of solution culture, so that, the physiological effects of ion concentrations and ratios of calcium to other ions on plant growth, could then be assessed free of any soil physical effects.

(4) Using the A and B horizons of Solonetzic soils to determine if results from solution culture (simulating displaced soil solutions) can predict plant growth performance in the soil. Also, to assess the affect of added gypsum, mixed into the soil, on plant growth.

LITERATURE REVIEW

I - SOLONETZIC SOILS

1. Occurrence and Formation

Solonetzic soils occur in all the five continents, being predominant in U.S.S.R., Australia, South America, China, Southern Africa, U.S.A., Eastern Europe and Western Canada. The Solonetzic Order in the Canadian System of Soil Classification is composed of three Great Groups, Solonetz, Solodized Solonetz and Solod (CDA 1976).

Solonetzic soils can occur on a variety of parent materials wherever brackish groundwater is, or was close to the soil surface. They have developed in areas of regional or local discharge of saline groundwater or by development from saline bedrock. In many cases the groundwater has become salinized by passage through brackish and marine water sediments. Due to the differential permeability of the parent material and difference in local relief, groundwater discharge is sporadic forming a mosaic of salinized areas rather than a continuum (Pawluk, 1973). This explains the occurrence of Solonetzic soils in association with soils not affected by salinity, such as Orthic Chernozems.

In the past, two theories have prevailed concerning

the primary method by which Solonetzic soils were formed (Tyurin et al.1960). The first theory contends that the initial stage is the presence of a saline parent material, followed by a second stage of leaching which causes a decrease in soluble salts and subsequent dispersion of the expansible sodium dominated clay minerals, such as smectite. The second theory maintains that saline groundwater, near the surface, in areas where evaporation allows sodium salts to occasionally rise to upper soil horizons, may cause sodium to become adsorbed onto soil colloids. Subsequent removal of excess salts by leaching, will gradually create conditions whereby dispersion can occur. It is generally considered that both theories may be correct in explaining the formation of Solonetzic soils. However, the first theory could only occur if the salt solution has very high amounts of sodium (up to 90%), as the presence of even small amounts of calcium or magnesium during desalinization, and dilution (under saturated conditions) of the soil solution will cause little sodium adsorption (Tyurin et al.1960). Such conditions may exist, for extremely high levels of soluble sodium, on outcrops of saline sedimentary material; it may then be concluded that the more universal process involved is the upward movement and concentration of salts from groundwater as outlined in the second theory. This allows upward movement of sodium under

unsaturated conditions causing substantial adsorption of sodium. Two main conditions then, must be met for pedogenesis of Solonetzic soils. Firstly, the presence of saline groundwater near the soil surface; and secondly alternate humid and dry periods; the latter causing a high evaporative demand. These two conditions will ensure capillary rise of sodium salts to form intermittent communication between the soil horizons and saline groundwater, without the build up of salts (Szabolcs 1971).

The Solonetzic soils of Western Canada have been subject to considerable research designed to understand the processes behind their development (Bowser 1961). The three Great Groups mentioned earlier are considered to be a genetic sequence because the Solod shows evidence of once being a Solonetz by presence of disintegrated humate stained peds and other features. The main processes involved are sodification (alkalization), desalinization and solodization. Sodification is the process whereby sodium becomes adsorbed onto soil colloids causing dispersion of the colloids and downward movement of soluble humates. Desalinization is the removal of salts by leaching, due to increased precipitation or lowering of the water table. In Alberta, glaciation allowed the gradual development of a new integrated drainage system which would result in a lowering of the water table (Pawluk 1973). Solodization

is the eluviation of the dispersed sodium clays and humates.

The Solonetz Great Group has a typical morphology due to sodification. A thin surface A horizon exists, which has been modified by plant growth, on top of a compact, columnar, impermeable, humate stained B horizon. Further desalinization and initiation of solodization forms a solodized Solonetz, which has a thicker A horizon due to more vigorous plant growth, plus an eluvial A horizon (Ae) caused by downward movement of sodium clay and humates, to give an illuvial columnar B horizon. An increase in vegetation coupled with a lowering of the water table, would encourage recycling of divalent cations to the surface horizons and a decrease capillary rise of sodium salts. This would result in the exchange and removal of sodium, either due to exchange by divalent cations or hydrogen from hydrolytic reaction of water with sodium clay. A Solod would then be formed having a thick A horizon, a humified eluviated A horizon (Ahe), and an eluviated A horizon developing at the expense of the B horizon. This process continues with the dark-coloured surface horizon following the eluviated horizon downward as the disintegration of the B horizon (calcium replacing sodium) occurs (Bowser 1961). Therefore, the sequence from Solonetz to Solod and resultant morphological differentiation of the soil profile occurs when the saline groundwater gradually ceases to influence the

soil profile. However, renewed groundwater activity and persistence of saline water in the solum can result in a reverse sequence and ultimate formation of a solonetz or even a saline soil (Tyurin et al.1960).

2. Chemical Characteristics of Solonetzic Soils in Western Canada

One dominant pedogenic feature found in the solonetz and Solodized Solonetz Great Groups is the layer of salt accumulation in the lower B horizon and C horizon (Bowser 1961). The predominant salts are sodium and magnesium sulphates (Cairns 1961), although bicarbonates and sulphate salts of calcium may also be present. Electrical conductivities of saturation extracts (in mmhos/cm at 25°C) range from 1 to 6 in the Bnt horizon and from 7 to 13 in the C horizon (Bowser et al 1962). Often the occurrence of readily soluble salts above less soluble salts provides evidence for the capillary rise of sodium salts, and their continuing effect on these soils (Cairns 1961).

High exchangeable sodium and often magnesium are found in Solonetz and Solodized Solonetz soils (Bowser et al. 1962; Cairns 1961; and Janzen and Moss 1956). An increase in exchangeable calcium of the Bnt horizon and decrease in exchangeable acidity of the A horizon occurs, through the Solonetz to Solod sequence (Bowser et al.1962). It has been suggested by Janzen and Moss (1956) that adsorption

of magnesium is favoured by the alkaline conditions found in the Bnt horizons of these soils. Evidence is given to show that magnesium adsorption is preferred over calcium adsorption by sodium clays at high pH.

In the A horizons pH may range from 5.0 to 6.5, while the range in the Bnt horizons is 6.6 to 8.0 (Bowser et al. 1962; Cairns 1961).

Although Solonchic soils have similar amounts of nitrogen as associated soils in Ap horizons of the same depth (Bowser et al. 1962), the distribution of nitrogen may differ between Solonchic and associated Chernozemic soils (Khan and Sowden 1972). The proportions of nitrogen as amino acid, amino sugar and ammonia in fulvic acids increased from Solonch through Solod to Eluviated Chernozem. Therefore, it was concluded that presence of salts had some effect on nitrogen mineralization. Biological release of nitrogen has been shown to be lower in Solonch than in solodic soils. This was considered a pH effect due to the generally low pH of the Solonch Ah horizon (Cairns 1973).

Soluble carbonates are not usually found in the Ap and Bnt horizons of these soils as the pH of the Bnt horizon rarely goes above 8. Soluble chlorides are found only in small amounts such as 1 to 2 milliequivalents per liter or less. Bicarbonates can range from 1 to 10 milliequivalents

per liter. The dominant anion is sulphate (Bowser et al. 1962).

High quantities of dispersed organic matter may be found in water extracts from Solonetzic soils. Research has shown little evidence of metallo-organic complexes, however, ions such as calcium may be in association with soluble organic forms (Khan 1970). Examination of humic acids extracted from Solonetzic and associated Chernozemic soils showed little variation in elemental composition, physical and chemical properties (Khan 1971).

The main criteria for classification of Solonetzic soils is the chemistry of the Bnt horizon. In the past, the amount of exchangeable sodium has been used to determine if a B horizon was considered Solonetzic. However, high amounts of exchangeable magnesium caused problems for the usefulness of this procedure, also there was often no relationship between water soluble sodium levels and exchangeable sodium. For instance, water soluble sodium percentages of over seventy were found when the exchangeable sodium percentage was only four (Ballantyne and Clayton 1964). Recent classification has used an exchangeable calcium to sodium ratio of less than 10 as a criterion for Solonetzic B horizons (CDA 1976).

In general, no free gypsum or calcium carbonates are found in the soil solum (Cairns 1961; Bowser et al. 1962). Parent materials often contain calcium and magnesium car-

bonates, therefore lime concentration horizons are found at depth depending on precipitation. Some gypsum or carbonates may be found in the solum of more saline sodic soils.

Although intensive research has not been done on availability of micronutrients, evidence indicates that they are not limiting for plant growth (Cairns 1973). Russian work has found that the total content of microelements in Solonetzic soils is close to that found in associated soils, also the distribution of microelements occurs according to genetic characteristics of the soil involved (Gamzikov 1969).

3. Fertility and Plant Growth

Fertility of Solonetzic soils usually increases along the Solonetz to Solod sequence. This sequence also shows an increase in water penetration, exchangeable calcium and decrease in exchangeable sodium and salinity. According to Tyurin et al.(1960) two main factors are responsible for limiting the fertility of these soils. Firstly, chemical factors such as salinity, low concentrations of bivalent ions and pH, may cause an adverse environment in the soil solution. Secondly, plant growth is retarded by poor physical properties such as low air-water permeability, hardness, high bulk density, lack of structure when moist, and swelling. Low levels of nitrogen availability

have also been observed (Cairns et al 1962).

It is the consensus of most sources that the main limiting factor for plant growth is adverse physical effects. Tyurin et al.(1960) in a review of Russian work indicated that unless exchangeable sodium exceeded 40 to 60%, little detrimental chemical effects occurred. At high levels of exchangeable sodium, calcium may become limiting. Therefore, the main effect of high exchangeable sodium was in creating adverse physical conditions. Similar conclusions are given by Szabolcs (1971) in a review of Solonetzic soils of Eastern Europe. Again, high exchangeable sodium affects physical and water regime properties. Available nutrients may be high but deficiency of available water, due to high exchangeable sodium, prevents nutrients from reaching plant roots.

However, both the above sources mention the adverse effects of salts in hindering uptake of water and nutrients by plants, as well as specific effects of salts. Salts may also have an adverse effect on microflora, although little is known in this area (Tyurin et al.1960). Cairns (1963) has shown that low microbial activity found in some Solonetz soils was due to lack of an available source of energy, which limited nitrogen mineralization.

High levels of exchangeable or soluble magnesium, in Solonetzic soils, have led to speculation that it may be

involved in affecting plant growth. Tyurin et al. (1960) stated that the effect of magnesium should be viewed from a standpoint of unfavourable chemical properties and needs further investigation. Cairns (1961) also notes the decrease in Mg/Ca ratio along the Solonetz to Solod sequence.

Natural vegetation on Solonetzic soils and especially along a Solonetz-Solod sequence is highly indicative of the retreat of salts and improved water regime. Solonetz soils have shallow rooting plants often xerophytic, along with deep rooting halophytes. As the groundwater ceases to play a role in dictating the type of vegetation, more legumes and tall grasses will predominate (Tyurin et al. 1960). This is an indication of the conditions which agronomic plants will be subjected to in crop production on Solonetzic soils.

Low levels of nitrogen reduce fertility on solonetz and Solodized Solonetz soils. These low levels are attributed to reduced mineralization due to low pH or presence of salts (Cairns 1973; Khan and Sowden 1972).

Moisture is certainly a limiting factor for optimum plant production on both Solonetzic and associated soils. However, Solonetz and Solodized Solonetz have the added disadvantage of salts which interfere with water uptake, and physical effects which interfere with water mobility. Therefore water availability is a major factor affecting

fertility of these soils.

In conclusion, the restrictions governing the fertility of Solonetzic soils tend to restrict the growth of crop plants mainly to the A horizon. This concept of 'flower pot agriculture' has been described previously by Cairns (1961).

4. Exchangeable Sodium

Much research has been done on the role of exchangeable sodium on plant growth. Under nonsaline conditions the amount of exchangeable sodium can be critical for certain crops (Bernstein 1975). Some crops such as beans (Phaseolus spp) are affected at exchangeable sodium percentages (ESP) of about 10. Most crops are not affected nutritionally until the ESP exceeds 25. Certain crops such as tall wheatgrass (Agropyron elongatum) can withstand an ESP of over 50 (Bernstein 1975). Tolerance of crops to high ESP has been related to low root cation exchange capacity (Bajwa and Bhumbra 1971); ability of plants to accumulate sodium in foliage rather than roots (Bower and Wadleigh 1948); low calcium demand (Pearson 1960; Tyurin et al. 1960); ion selectivity mechanisms (Russell 1970) and ability of plants to absorb nutritionally adequate levels of calcium and magnesium from low concentrations of these elements in the soil (Bernstein 1975).

Early Russian work indicated that the deleterious

effect of exchangeable sodium on cereals occurred when the ESP exceeded 50 (Ratner 1935; 1938). At these high levels of exchangeable sodium a competitive effect between roots and soil colloids for calcium occurs. This can result in desorption of calcium from the plant roots by the soil colloids (Tyurin et al. 1960).

American work also indicated a breakdown in the calcium regime and reduction in yields when the ESP was high. Magistad (1945) in a review on sodic soils indicated that an ESP above 40 was deleterious. Other work by Bower and Turk (1946) with alfalfa (Medicago spp) showed that applications of calcium gave increased yields and calcium levels in the foliage.

More intensive treatment has been given this problem by Bernstein and Pearson (1956). They found no direct relationship between composition and yield as ESP increases; that is a decrease in growth showed no increase of sodium content of the foliage. They concluded that sodium accumulation in the roots may be a factor in affecting water absorption. Work with cereals confirmed earlier Russian work, indicating that wheat (Triticum spp) and barley (Hordeum spp) were not reduced in yield until the ESP exceeded 40 to 50 (Pearson and Bernstein 1958). Yield was related to exchangeable sodium rather than absolute sodium in the soil, although this concept was later modified to

include the concentration of sodium in the soil solution (Bernstein 1975). Recent USDA publications (Pearson 1960) advise producers to use low calcium demanding plants on soils with high ESP. They also state that retarded growth of crops below an ESP of 20 is due to physical effects, which is further aggravated by nutritional effects as the ESP increases. Increasing ESP has been shown to cause an increase in absorption of sodium and decrease in absorption of calcium, potassium and micronutrients. Although the latter decrease may be due to increase in pH (Bains and Firman 1964).

Research has also been concentrated on soils with high ESP plus high exchangeable magnesium. Many Solonetzic soils of Western Canada would fall into this category (Ballantyne and Clayton 1964; Bowser et al. 1962; Cairns 1961). High exchangeable magnesium may be detrimental if high ESP is also present, as this combination is usually indicative of low exchangeable calcium (Joffe and Zimmerman 1944; Russell 1970). A high exchangeable magnesium to calcium ratio can also have adverse effects on plant growth, resulting in calcium deficiency (Joffe and Zimmerman 1944; Vlamis 1949). Russian work has concentrated on the extent of sodium saturation of humic acids (Tyurin et al. 1960). They claim that high sodium humate levels can lower the tolerance of plants to ESP; the sodium humates being more toxic than the mineral constituent.

In summary then, the relatively low ESP of Solonetzic Bnt horizons in Western Canada (between 7 and 30) would indicate only small nutritional limitations exist. However, combinations of medium ESP and high exchangeable magnesium does exist and could provide nutritional problems.

5. Amelioration

Methods of amelioration are usually based upon natural pedogenic processes which occur along the Solonetz to Solod sequences. The aim of amelioration is to hasten these processes, so that more favourable conditions are created for crop growth. Once these are achieved, crops will continue the process by recycling divalent cations from lower horizons (White 1971) and improving porosity and soil structure by more vigorous root growth, which in turn gives greater aeration and water infiltration (McNeal et al. 1966). The end result is a soil solodic in nature, showing a decrease in exchangeable sodium and magnesium and an increase in exchangeable calcium. At the same time all previously mentioned adverse physical and chemical effects are vastly improved. All this of course, is dependent on the principle of continuing groundwater retreat and disconnection from the soil solum, as normally occurs along the Solonetz-Solod sequence.

The application of calcium compounds is usually recommended for amelioration of Solonetzic soils. Gypsum

($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is often used due to its abundance as a by-product of various industries and thus economical. Three main disadvantages can be mentioned in relation to use of gypsum. Firstly, it has a relatively low solubility in the soil which is further reduced by high amounts of sulphate ions present in the soil solution and subsequent common ion effect. Solubility can also be reduced by protective films of CaCO_3 or humate adsorption onto gypsum particles (Tyurin et al.1960). The result of decreased solubility, is that the desired exchange of sodium by calcium is impeded. Further to this, the gypsum fails to provide a sufficiently strong electrolyte solution to maintain water infiltration through sodium saturated clays, which tend to disperse under low concentrations of electrolytes. This however, may not be a problem if the ESP is below 20 (Graveland and Toogood 1963). The second disadvantage of using gypsum is that it lowers the pH in the already acidic A horizon (Cairns 1972). A third disadvantage is that a yield decrease can occur for a few years after application of the gypsum. This has been noted by Cairns (personal communication). Russian workers claim that the decreased growth is due to the slow adaptation of microorganisms to the new environment caused by displaced sodium. This results in decreased mineralization (Tyurin et al.1960). However, application of gypsum plus nitrogen will correct this decrease (Carter et al.1977).

Gypsum has been used successfully for crops which have a high calcium demand such as legumes and other dicotyledons (Poonia and Bhumbla 1973a). Also, in saline-sodic soils, where maintenance of adequate electrolyte solutions is not a factor, applications of gypsum can improve yields and increase calcium and potassium uptake (Poonia and Bhumbla 1973b). In instances where calcium is not a nutritional factor, applications of gypsum may only increase uptake of calcium and not increase yield (Szabolcs et al. 1957). However, if calcium is a limiting nutritional factor, then an increase in soluble calcium may increase yield even if no change in exchangeable sodium takes place (Bronson and Fireman 1960; Obrejanu et al. 1970). This of course will not occur if other limiting factors exist.

In order to render gypsum more effective, work has been done on applying gypsum with the seed. Small amounts of gypsum (10-15% of gypsum equivalent) have increased yields of cereals by 8-25%. The reasons given for this increase were exchange of sodium by calcium, amelioration of nutritional calcium limitation and improvement of physical and biological soil properties in the seed zone (Abraham and Szabolcs 1964; Abraham 1965). However, other research has shown that long term applications of gypsum with the seed gave little overall yield increase (Sambur 1963). This indicates the danger of generalizing from short term

experiments. In the case of legumes (Phaseolus spp) increases in growth, nodulation and nitrogen fixation have been observed when CaCO_3 or CaSO_4 were pelleted with the seed on a saline-sodic soil (Chhankar et al.1971).

The use of gypsum in combination with other salts has been considered in attempting to overcome the disadvantages of gypsum. Tyurin et al.(1960) mentions that use of sodium chloride will increase the solubility of gypsum and help maintain sufficient electrolyte concentration for water infiltration. Similar results are given by Reeve and Bower (1960) who used high salt waters to maintain flocculation. The saline solution contained high amounts of divalent ions, which according to the 'valence-dilution' effect would be preferentially adsorbed over mono-valent ions at high dilutions. Another factor to be considered is that mixing the gypsum with other ions will cause incomplete exchange of sodium ions, so that calcium will be spread over a greater depth and not left to saturate only the surface horizons (Bolt 1976). Carter et al.(1977) used gypsum in combination with ammonium nitrate to achieve gypsum penetration. Ammonium nitrate will increase gypsum solubility and was shown earlier by Cairns and van Schaik (1968) to aid water infiltration. In all these techniques of improving gypsum penetration, the use of irrigation was often an important aspect of supplementing the usually low precipitation.

Mobilizing the natural calcium supplies of the soil is another ameliorative method. In soils which contain CaCO_3 in the surface horizon, the application of compounds (e.g. sulphur compounds) to lower the pH, will cause more solubilization of CaCO_3 . Another method of utilizing native calcium is by deep-plowing. This method can only be used on soils which have a salt accumulation (gypsum-lime horizons) at shallow depth. Soils which have high sodium to calcium ratios and low extractable calcium in the lime-salt horizon do not lend themselves to deep plowing (Cairns 1976). Russian work has indicated that mixing the salt layer with the Bnt horizon will lead to a favourable ratio of sodium to calcium for exchange displacement of sodium (Tyurin et al. 1960). Canadian work also indicates that mixing the horizons causes a decrease in the sodium to calcium ratio, improved water infiltration, increased root area, and a decrease in exchangeable magnesium (Bowser and Cairns 1967). Yields of alfalfa were doubled whereas cereals showed small increases. Deep plowing has shown promise for ameliorating soils with very unproductive B horizons (Cairns 1971a). Further work showed that mixing horizons stimulates microbial activity and thus increases nitrogen availability (Cairns 1972). This was brought about by an increase in pH which allowed greater symbiotic nitrogen fixation and nitrogen mineralization. However,

horizon mixing can be detrimental, as the beneficial physical effects of the humified A horizon are often lost when mixed with a B and C horizons, resulting in seedbed problems (Cairns 1976).

Although it is generally thought that the main processes needed for amelioration are decreases in sodium to calcium ratios and increased water infiltration, some research has shown that other limiting factors are involved. Long-term fallowing gave increased productivity and improved nitrogen status, although a concomitant loss of extractable calcium and gain of extractable sodium in the A horizon occurred (Cairns 1970).

Low levels of nitrogen have been observed on sodic soils (Cairns et al.1962; Tyurin et al.1960). Russian work has shown that improvement of the nutritional regime, by adding nitrogen will enhance the salt tolerance of certain crops (Tyurin et al.1960). Canadian work went further and demonstrated that application of nitrogen fertilizers improved yields (Cairns et al.1962); increased root growth, uptake of nitrogen and potassium, moisture extraction and sodium leaching (Cairns et al.1967); and increased soluble calcium and potassium and over a long period of time gradually reduced exchangeable sodium below 15% to a 30cm depth (Cairns 1971b). Effect of nitrogen fertilizers on root growth was especially significant. Root mass was doubled

along with increased activity within and below the Bnt horizon; evidently the hard B horizon is not always a barrier to root growth (Cairns et al.1976). Other work confirms the above results and stresses the ability of nitrogen fertilizers to increase yield and uptake of nitrogen, phosphorus, potassium and calcium (Abrol 1968; Chander and Abrol 1972; Latkovics 1965; Szabolcs and Latkovics 1967; Zayats 1972). However, the beneficial effects of ammonium nitrate, especially the ammonium ion on soil structure may be short lived (van Schaik and Cairns 1974). This necessitates the use of calcium compounds to give permanent effects. Also, high amounts of ammonium nitrate by rapidly increasing water infiltration may encourage greater sodium adsorption, as the ammonium ion displaces calcium from the soil colloids and in turn may be displaced by sodium (Carter et al.1977).

Phosphorus limitations have often been cited as a possible nutritional factor on sodic soils (Krogman and Milne 1968). Other observations show that soluble phosphates may increase with depth (Cairns et al.1962). Russian work indicates that all genetic horizons contain adequate phosphorus for plant growth, except some lower horizons or subsoils (Tyurin et al.1960). It may be that low phosphorus levels are a regional problem as Tyurin et al. (1960) reviewed work which showed phosphorus limitations were common to both Solonetzic and associated Chernozemic

soils. However, factors common to sodicity may slow phosphorus mineralization as it does with nitrogen. Certainly a high pH found in the B horizon does hinder availability of phosphorus (Srivastava et al.1971).

In conclusion then, the amelioration of Solonetzic soils involves the correction of nutritional and physical effects. Invariably, the methods used in amelioration cause increased water infiltration which may allow renewed groundwater activity to occur, in the soil solum. Therefore caution should be used to prevent secondary salination by a rising water table (Tyurin et al.1960).

II - FACTORS AFFECTING PLANT NUTRITION

1. Ion Uptake From the Soil

Controversy exists as to how plant roots obtain nutrients from the soil, which has an important bearing on the ability of Solonetzic soils to provide nutrients for plant growth.

Contact exchange, the ability of ions to move from soil colloids to the root cation exchange sites, is often cited as an important factor in ion uptake (Jenny 1966). The actual mechanism has been described as overlapping of oscillating ions in the diffuse double layer of root cation exchange sites and soil colloids (Lagerwerff 1960). Other sources claim that the composition of the soil solution

phase fully characterizes the environment of plant roots (Brewster and Tinker 1970; Elgably 1955; Lagerwerff 1958; Olsen and Peech 1960).

Contact exchange differs from exchange diffusion in that the former envisions actual contact between root and soil colloid, while the latter implies contact of the diffuse double layers only. Contact exchange has been shown to occur between root plugs and iron oxides (Charley and Jenny 1961). Work with chelates has also shown that chelated iron can be directly exchanged for ions on root surfaces (Wallace and Mueller 1976). Similar results occurred with calcium ligands when the concentration of ionic calcium was at a low level (Malzer and Barber 1976).

Models of how roots obtain ions differ according to the acceptance or rejection of exchange diffusion. Some sources state that plant nutrients reach roots by root interception (involving exchange diffusion), mass-flow and diffusion (Barber et al. 1963). Moreover, they claim that exchange diffusion will provide much of the calcium and magnesium, while diffusion will account for the nitrogen and phosphorus (Barber et al 1963; Oliver and Barber 1966). Others would claim that only mass-flow and diffusion is involved, as root interception is really only another aspect of diffusion (Brewster and Tinker 1970). As the apical region of the root is pushed into unexploited parts of the

soil volume, the original concentrations of ions are rapidly depleted resulting in changing rates of diffusion (Clarkson 1974). Therefore the dynamic nature of diffusion could explain the mechanism of root interception.

Further work to determine if exchange diffusion was a factor in root uptake has been done by Barber et al.(1971). They noted that the calcium to strontium ratio was different in solution than on the exchange complex, due to preferential adsorption of calcium over strontium. It is already known that uptake of strontium and calcium occurs in the same ratio as that found in the root medium. Therefore utilizing this principle, plants were grown in soil and the strontium to calcium ratio of the leaves compared to the ratio in solution and on the exchange sites. It was found that the ratio in the leaves reflected that of the exchange sites when mass-flow was kept to a minimum by relatively high humidity. In cases where mass-flow was high the ratio reflected that of the soil solution (Bole and Barber 1971).

Other research has shown that the difference in ability of plants to take up cations from the soil was controlled by the cation exchange capacity of the root (Drake et al.1951). However, calcium usually predominates on the root cation exchange and yet potassium is accumulated by cells at rates some 20-60 times greater than those for calcium (Bowling 1976). This would indicate that there is

no relationship between exchange capacity of the root and subsequent accumulation in the plant. However, divalent ions would only predominate on the root exchange sites under dilute conditions. According to the valence-dilution effect, mono-valent ions would dominate under high sodium saline conditions (Wiklander 1966).

Recent research into root physiology of cereals has found the presence of rhizoplane fibril aggregates between the root cap and root hair zone. They are composed of poly-glacturonic acids, and due to their small size (20nm) have been postulated to play a role in accumulating bound cations from the soil exchange sites (Leppard and Ramanmoorthy 1975).

In summary, the mode of ion absorption is an important factor for Solonetzic soils and plant nutrition. Soil solutions of Solonetzic soils due to colloid exchange sites, solid salts and adsorbed salts, often have different ratios of ions in solution phase than those on the adsorbed phase (Khan and Webster 1966). Also, at low moisture contents the diffuse double layer volume of the soil colloids may take up a large portion of the smaller pore space (Bolt 1976). Soils of low calcium concentration depend heavily on adequate diffusion to supply sufficient calcium for plant needs (Clarkson 1974). Soils which fail to satisfy soil solution equilibria due to impeded diffusion, may

cause conditions to exist where exchange diffusion gains in importance (Lagerwerff 1960). In other words, exchange diffusion is important where equilibrium in the soil solution becomes difficult to maintain due to low diffusivity.

2. Salinity

Several mechanisms whereby salts affect plant growth have been observed. Firstly, salts can decrease water availability to roots due to adverse water-potential gradients. To some extent, this may be overcome by osmotic adjustment within the plant. This is achieved by increasing the sap concentration (decrease osmotic potential). However, a time lag exists between osmotic adjustment and increasing salinity levels of the soil solution. Also, inability to absorb salts at high enough rates to counteract the subsequent dilution from adjustment and growth, will still ensure some growth reduction (Bernstein 1975; Meiri and Shalhevet 1973). Further to this, excess salts can build up in cell walls as the supply exceeds the rate of ion uptake by cells. This will result in reduction of osmotic potential of cell walls and subsequent dessication of the vacuole (Meiri and Shalhevet 1973).

A second mechanism of salts in affecting plant growth is by changing the balance between root and shoot hormones. Increasing water stress will increase abscisic acid production (growth inhibitor) and decrease cytokinin levels

(growth promotor) with an overall reduction in growth (Bernstein 1975; Poljakoff-Mayber and Gale 1975; Meiri and Shalhevet 1973).

Other mechanisms are: damage to plant cells and cytoplasmic organelles by accumulating salts; interference with normal metabolism, such as increasing respiration and reducing photosynthesis; and alteration of enzyme activity or structure.

External factors may also increase or reduce salinity effects. High temperatures will increase salinity damage, although some results indicate only a summation of temperature and salinity effects occur rather than an interaction. Other external factors such as high levels of radiation and low air humidity can increase salinity effects. These latter two factors are involved in controlling transpiration rates which can alleviate or increase water imbalance (Poljakoff-Mayber and Gale 1975).

Specific ion effects can also reduce plant growth (Ayoub and Ishag 1974; Lagerwerff and Eagle 1961; Wadleigh and Gauch 1942). Ions such as sodium, chloride, boron, bicarbonate, magnesium and sulphate may cause specific ion effects. The last two are important as their specific toxic effect is mainly indirect, in that sulphate will restrict calcium uptake and promote sodium uptake; while magnesium will reduce calcium uptake and cause calcium deficiency (Meiri and Shalhevet 1973).

Variations in plant response to salinity according to Poljakoff-Mayber and Gale (1975) are due to five factors:

1. ability to exclude salt from sensitive tissues (compartmentalization);
2. ability to achieve complete osmotic adjustment;
3. inherent stability of membranes, enzymes and macromolecules to high ionic concentrations;
4. ability to manufacture factors to stabilize macromolecules; and
5. ability to apply other adoptive modifications.

According to Greenway and Rogers (1963) barley (Hordeum vulgare) can accumulate ions in the foliage as an adaptive mechanism for growth on saline soils.

An important aspect, concerning plant growth, in saline solutions is ion absorption. Research has shown that potassium can be absorbed more efficiently in saline solutions by halophytes than glycophytes (Epstein 1969). Sufficient potassium could be absorbed even in high sodium solutions as long as calcium was present (Rains 1972). High ion absorption will result in an imbalance of cations and anions within the plant. As anions become incorporated into metabolites, the excess cations which remain need to be balanced. Therefore, ability for organic acid synthesis allows maintenance of intercellular ionic balance and ion absorption in halophytes. Further work with halophytes has shown that ion absorption in saline solutions stimulates respiration. It is thought that the extra energy required

for ion absorption influences the rate of respiration. Therefore, ability for high ion absorption, organic acid synthesis and regulation of respiration are mechanisms necessary for growth in saline solutions (Rains 1972).

Calcium also plays a role in regulating ion transfer in saline media (Bernstein 1975: Poljakoff-Mayber and Gale 1975; Rains 1972). The actual role of calcium is explained in another section.

3. Solution Culture

Soil-root associations are difficult to study due to the many factors involved. Since many variables are involved, methods have been adapted which are more conducive to experimental control. One such method is hydroponics or solution culture, which enables intensive study on the effect of mineral concentrations and ratios of ions for plant growth (Epstein 1972).

Several disadvantages can be mentioned in regard to solution culture. First of all, root hairs commonly present in soil-grown plants are frequently absent on roots grown in water culture. Secondly, the microflora of the root surface will differ, which could have a bearing on plant growth. Thirdly, the mantle of mycorrhizal fungus which usually develops in soil-grown roots will be absent (Bowling 1976). These factors are of great importance for study of certain elements such as phosphorus but will not

be so limiting for study of major cations.

Certainly the advantages of solution culture lie in the area of assessing the physiological role of a certain element, determining interrelationships between certain elements, and in characterizing nutrient deficiencies (Gauch 1972). In Solonchic soils it helps determine whether the beneficial effects of calcium enrichment are partly nutritional or entirely due to improving the physical properties of the soils.

III - CALCIUM

1. Nutritional Role

Although calcium is regarded as a macronutrient only small amounts are actually needed for plant growth. Dicotyledons usually have greater concentrations of calcium in their foliage than monocotyledons but can absorb calcium at a greater rate (Loneragan 1968). Therefore as long as a constant level of calcium is maintained in the root environment, the plant will have adequate calcium. This will have practical applications in soils of relatively low calcium and impeded diffusion. Another factor concerning calcium nutrition is the difficulty with which calcium is retranslocated within the plant. Therefore, growing tips must always have an adequate supply of calcium in the root environment (Fong and Ulrich 1970; Loneragan and Snowball

1969). Moreover, this indicates that calcium deficiency can occur at growing points even though other parts of the plant have adequate calcium. This was shown by Marschner and Richter (1974) who exposed plant roots to different levels of calcium. They found that root tips would develop calcium deficiency even though the basal roots were supplied with adequate calcium. Therefore no movement of calcium from basal roots towards the growing tip occurred.

Calcium plays an essential role in cell wall formation. Deposition of calcium pectate in the cell wall increases the rigidity and hardens the structure. However, under low calcium levels, normal cell walls can still be produced. This indicates that deposition of calcium pectate may not be that important and that the role of calcium may be more complex (Wyn Jones and Lunt 1967).

Model systems of membranes indicate the probable role of calcium in stability of membrane constituents. Constituents of membranes like phospholipids can have their surface tensions reduced by binding of calcium ions (Wyn Jones and Lunt 1967).

Chromosomes and nucleic acids such as DNA and RNA also form complexes with calcium. The calcium ions function as ionic bridges, which can easily be removed by EDTA. It would seem as if calcium prevents dispersion and may also confer specific configuration to nucleic acids (Wyn Jones and Lunt 1967). These authors also give extensive evidence

of calcium involvement in enzyme activity or as an enzyme component.

2. Physiological Role

Calcium has long been known to protect cell membrane integrity (Epstein 1961, 1962, 1972; True 1922). The requirement of calcium in the root medium for actual growth purposes is actually very low. This was demonstrated by Wallace et al. (1966, 1968) who grew plants in solution cultures with 1/50 or less calcium than that found in Hoagland solution (Hoagland solution contains 5mM calcium). Plant growth was normal as long as copper, iron, manganese, zinc, strontium, magnesium and other ions were kept at low concentrations. Further research showed that calcium levels required at the root site can be low, as long as other cation concentrations are also low (Lund 1970).

The actual mechanism involved in calcium protection of membranes is still not clearly understood (Poljakoff-Mayber and Gale 1975). True (1922) found that very low levels of calcium in solution allowed lack of retention and leaking of ions from the roots into solution. According to Jennings (1969) calcium reduces ion leakage from cells by filling pores in the plasmalemma. Calcium has been shown to decrease the permeation of hydrated mono-valent cations (e.g. sodium) across the plasmalemma, but will stimulate the permeation of smaller hydrated mono-valent cations such

as potassium (Jacobsen et al. 1961; Waisel 1962). This ability of calcium to accelerate potassium uptake was first discovered by Viets (1944) and is commonly referred to as the 'Viets effect'.

Calcium has been found to moderate the influence of salinity on ion uptake and plant growth. Proportions of calcium in the medium that are adequate under nonsaline conditions become inadequate under saline conditions, and may result in salinity-induced calcium deficiencies (Bernstein 1975). Growth of beans (Phaseolus vulgaris) a salt sensitive plant was severely repressed at 50mM NaCl and low calcium levels; increasing the calcium level restored growth and prevented uptake of high amounts of sodium. Again, calcium protection of the plasmalemma in modifying the effect of other ions (especially sodium) was thought to be occurring (LaHaye and Epstein 1969). Other work by Hyder and Greenway (1965) showed that barley (Hordeum vulgare) was sensitive to sodium concentrations when calcium levels were low. Further to this, increasing concentrations of sodium at low calcium levels, affected the relative amounts of calcium, sodium and potassium absorbed by barley (Elzam 1971). High amounts of hydrogen, aluminum and ferric ions can also suppress calcium uptake; improvement of the calcium status can overcome this inhibition and restore the absorption mechanism of the plasmalemma

(Clarkson and Sanderson 1971; Rains et al. 1964; Tooper and Leach 1957).

Growth of cotton (Gossypium hirsutum) in saline solutions can also be improved if adequate calcium is supplied. Increasing salinity was found to reduce calcium uptake and impair cell wall formation (Gerard and Hinajosa 1973). For instance, at a salinity level of -0.8 bars, 0.25mM of calcium was needed; at -6.6 to -12.9 bars, 5mM of calcium was needed. Failure to supply these levels of calcium resulted in reduced root vigour, growth and cell wall formation (Gerard 1971; Gerard and Hinajosa 1973). This work also indicated, that the ameliorative effect of added calcium will only occur in low calcium solutions where calcium is a limiting factor. Further addition of calcium cannot be expected to further ameliorate salinity effect or increase yield.

Work with two species of wheatgrass (Agropyron) which differed in their salt tolerance, gave results indicating that low salt tolerance was correlated with low levels of calcium in the root (Elzam and Epstein 1969). The ability of roots to maintain adequate calcium uptake under increasing salinity levels, was considered a key element in response of these plants to salinity.

Roots are usually sensitive to calcium deficiency, and therefore have been used for studies into the physio-

logical role of calcium. Tanaka and Woods (1972, 1973) working with oat seedlings (Avena spp) found that suppressed elongation of root hairs in low calcium solutions was due to toxicity of other ions rather than lack of calcium. Additional calcium was needed to ameliorate these toxicities.

According to Epstein (1972) the physiological role of calcium is to safeguard the selective permeability of the plasmalemma, especially against toxicity of other ions. Low calcium levels in solutions will impair ion transport mechanisms and retention of ions (Haynes and Robbins 1948). This can be shown by excluding calcium and observing ions such as potassium diffuse out of the cell into the solution. Addition of calcium will cause unidirectional absorption of potassium against the diffusive gradient (Epstein 1972).

Several workers have investigated the agronomic significance of the physiological role calcium plays in the soil solution. Howard and Adams (1965) found that for penetration of primary cotton roots into subsoils, a calcium to total-cation ratio above 0.10- 0.15 was a critical factor rather than calcium content per se. Geraldson (1970, 1971) found that the optimum nutrient solution should contain 15% calcium. For instance, when calcium levels went below 150 ppm of a 1000 ppm solution growth reduction occurred. Moreover, when calcium levels were kept at 150 ppm and the

total salt concentration taken over 1000 ppm, again, growth reduction occurred. However, calcium deficiency did not occur until the percentage calcium fell to about 5%. This then, demonstrates the extra calcium needed in the root environment to maintain optimal yields.

Soils with high levels of soluble sodium and low soluble calcium have been shown to give reduced yields (Ballantyne 1962). Observations indicated that it was not the high levels of sodium but a combination of high sodium and low calcium. These conclusions were also indicated by Kelley (1963).

In summary, then, calcium has an ameliorating effect against the toxicities of other ions in the root environment. This has special significance for plant growth if the soil solution has inadequate amounts of calcium. This often occurs under saline conditions (Poljakoff-Mayber and Gale 1975).

3. Interactions with other Ions

Much work has been done on the effects of ions on plant growth. Unfortunately, only single ion solutions have been used which makes it difficult to relate the results to natural conditions.

Studies with sodium and calcium on growth of root hairs, indicate that high concentrations of sodium cause plasmolysis (cell bursting) of root hairs to occur. The

occurrence of plasmolysis can be reduced by addition of calcium (Ekdahl 1953). Increasing SAR at low salinity levels gave a decrease in yield of vegetables due to insufficient amounts of calcium (Lagerwerff and Holland 1960).

Kinetic studies have shown that potassium and sodium are competitors for the same binding site in ion uptake. Therefore high sodium levels can cause a decrease in potassium uptake (Huffaker and Wallace 1959). Conversely, this concept has led to the idea of increasing potassium levels to discourage sodium uptake in saline solutions (Heimann 1959). Further research showed that uptake of sodium was influenced by levels of potassium, and that uptake of potassium was more dependent on the potassium concentration (Heimann and Ratner 1962). However, selective uptake of potassium is dependent on availability of divalent cations (Pitman 1975). In the experiment by Heimann and Ratner (1962) high levels of calcium were used. Elzam (1971) showed that the level of calcium not potassium was important to maintain potassium uptake. Increasing sodium was found to depress calcium and potassium uptake, while increasing the calcium increased potassium and decreased sodium uptake.

Field experiments on Solonchic soils have shown that applications of nitrogen can increase the potassium and decrease the sodium content of the foliage (Cairns et al.

1967; Cairns 1971). This may be a result of a greater root cation exchange due to nitrogen fertilization (Drake and White 1961); increase in organic ions in the plant due to improved nitrogen status and subsequent greater cation uptake (Haeder and Mengal 1971); or retreat of sodium by increased leaching to allow less competition between potassium and sodium for uptake mechanisms.

Calcium deficiency has been related to the ratio of calcium to magnesium or total ions and was not related to the absolute concentration of calcium (Bamford 1931). Some confusion exists in indicating what causes the injury to plants at high magnesium to calcium ratios. Either calcium deficiency or magnesium toxicity occurs. Trelease and Trelease (1931) choose the latter, while Mostofa and Ulrich (1976) prefer the former. However, in both cases normal growth can be restored by increasing the calcium. Lyle and Adams (1971) found that plant growth was reduced whenever the magnesium to calcium ratio went above 1.3 or if the calcium to total cations went below 0.1. Mostafa and Ulrich (1976) also show a critical magnesium to calcium ratio of 1.3.

In a review on ion activity and plant uptake, Khasawneh (1971) concluded that attempts to find a critical magnesium to calcium ratio were limited, by the fact that ion antagonistic effects on calcium are the result of the total cation

concentration in solution and are not restricted to the magnesium concentration. The review gives some magnesium to calcium ratios found to be critical, and how they differed from one another. However, if expressed as the ratio of calcium to total cations as shown by Howard and Adams (1965) a critical and consistent ratio was found.

Magnesium has long been known for its toxic effect to plants (Gauch and Wadleigh 1944). This toxicity can be ameliorated to some extent by calcium; hence the importance of the magnesium to calcium ratio. Moore et al. (1961) showed that a large fraction of magnesium absorption could be blocked by small amounts of calcium. Conversely, magnesium can interfere with calcium uptake (Mostafa and Ulrich 1976).

Studies with native vegetation on high magnesium soils (Serpentine soils) would confirm the above results. Tolerance to the high levels of magnesium was due to the ability of absorbing greater amounts of calcium (Walker et al. 1955).

4. Factors Affecting Activity in the Soil Solution

The activity of an ion is described as the 'effective concentration' and takes into consideration interactions of ionic calcium with other ions in solution, which would tend to reduce the concentration of free ionic calcium over its original concentration (Adams 1971a).

Solutions with calcium and magnesium sulphates will tend

to have a certain percentage of the calcium and magnesium tied up as ion-pairs (Adams 1971b). As the ionic strength of the solution increases the percentage of ion-pairs will increase (Bennett and Adams 1972). This is due to the concentration of sulphates being greater than the concentration of calcium and magnesium. For instance, between 25-48% of calcium and magnesium can exist as ion-pairs depending on the sulphate level (Nakayama and Rasnick 1967; Tolur et al., 1968). Therefore concentrations of free ionic calcium can be drastically reduced under the above conditions. Further to this, increased salinity levels in the soil solution due to salts or decrease in moisture has been implicated in decreasing the activity coefficients of divalent ions faster than monovalent salts (Geraldson 1957).

An alternate method by which availability of calcium can be reduced is by complexing with soluble organic matter. High amounts of calcium have been found as calcium-organic complexes (Dixt and Lal 1974; Nightingale and Smith 1967). However, research in Western Canada found little evidence for complexing (Khan 1970).

IV - SOIL SOLUTION DETERMINATIONS

The soil solution is a quasi-equilibrium solution of electrolytes that occurs in the soil under unsaturated moisture conditions (Pearson 1971). Various methods have evolved to

derive the concentrations and proportions of electrolytes found in the soil solution. Moss (1969) classifies these methods into direct or indirect groups. Direct methods are concerned with actual measurement of concentrations and proportions, after extraction. They include pressure membrane, centrifugation, displacement, filter-paper, centrifuge filter paper and ceramic points. According to Moss (1969) all direct procedures which utilize membranes or pressure may cause alteration of the equilibrium between soil and soil solution. Also, the application of pressure can cause encroachment and interaction of neighbouring double layers. This could cause some of the ions from the double layer to be included in the filtrate. The consensus of many workers is that the displacement technique is the best method for direct determination of the soil solution (Adams 1971a; Moss 1963, 1969; Parker 1921; Pearson 1971; Reitemeier 1946).

Indirect procedures to determine composition of the soil solution are as follows: water extract, extraction in calcium chloride and quantitative equilibrium methods (Moss 1969). The latter method has been used with some success in non-saline soils. Most of the work has concentrated on the ratio of potassium to other ions in solution. Moss (1963) showed that the ratio expressed in negative logarithms of $pK - 1/2p$ ($Ca+Mg$) was constant only over the field range of moisture

(-15 to -1/3 bar). Further work, comparing quantitative relation and displacement methods gave results that were in good agreement (Moss 1969). Therefore studies restricted to only two cations can be successfully used to relate solution content at one moisture level to another moisture level (Pearson 1971). However, estimation of more than two ions, or complete ionic content is not possible by indirect procedures (Adams 1971b).

Such indirect methods as saturation paste extracts, to predict soil solution composition have not been entirely satisfactory (Pearson 1971). Research has shown that different phases can become involved in both saline and non-saline soils, and cause changes in soil-soil solution equilibria (Khan and Webster 1966; Moss 1963). This is further explained by Pearson (1971) in the context of multiple equilibria. Electrolytes are derived and in equilibrium with free soluble salts, adsorbed salts, precipitated compounds and exchangeable ions. Further to this, extraction at saturation paste entails dilution of the soil system and subsequent 'dilution-valency effect' (Moss 1963). Therefore, an accurate estimation of the soil solution at field moisture necessitates extraction within the field moisture range.

The displacement technique offers the least chance for change in solution composition as no membrane or excessive

pressure is used. It has been shown that successively displaced soil solution fractions have the same composition and are free from any of the displacing solution (Adams 1971a; Moss 1963, 1969; Parker 1921; Pearson 1971). The displaced soil solution from different samples of the same soil, at the same moisture content has the same composition (Moss 1963; Parker 1921). Soils can also be displaced at various moisture levels between -15 and $-1/3$ bar. In the case of $-1/3$ bar levels, little dilution of the soil solution occurs. However, displacement of a soil solution below $-1/3$ bar would mean that the lowest portion of the soil would be in excess of $-1/3$ bar before any solution drips from the displacement tube. A rapid equilibrium change would, therefore, cause displaced soil solutions, at various moisture contents (below $-1/3$), to be of identical composition. Research has shown, however, that equilibrium is not readily attained; so that displaced soil solutions at different soil moistures differ in their chemical composition (Adams 1971a; Moss 1963; Parker 1921). Moreover, the different soil solutions displaced at various moisture levels between -15 bar and $-1/3$ bar conformed to the ratio law. Various amounts of soil solution can be displaced before contamination with the displacing solution occurs.

Most displacing solutions used are miscible with the soil solution. Moss (1963, 1969) used ethanol, while

Adams (1971a) used a saturated gypsum solution. According to Moss (1963) the mechanism behind the displacement technique is piston displacement. However, extensive research into miscible displacement indicates that some mixing occurs between the soil solution and displacing solution (Biggar and Nielson 1967). Therefore, complete displacement of the soil solution by the displacing solution cannot occur.

Mixing of the soil solution and displacing solution is brought about by differences in pore size and subsequent velocity differences, and because of diffusion (Biggar and Nielson 1967). Displacement usually gives the typical sigmoid shaped breakthrough curve of the displacing solution, whereby increasing amounts of the displacing solution occur in the effluent. However, a certain amount of the original soil solution (pore volume) can be displaced before the mixing front becomes evident in the effluent. Therefore, a certain volume of soil solution, free of displacing solution can be obtained by miscible displacement (Biggar and Neilson 1967; Cary and Horton 1968).

Examination of the soil solution (free of the displacing solution) in successively displaced fractions indicate a constant chemical composition (Adams 1971a; Moss 1963; Parker 1921). If the soil solution displaced characterizes the whole soil solution or only that found in larger pores, depends very much on the velocity of the displacing solu-

tion and the original water content of the soil. Low velocity and use of unsaturated soils will cause slower displacement and greater opportunity to displace smaller pores (Biggar and Neilson 1967). However, treatment of the displaced soil solution as an average of the pore size or more characteristic of the larger pores, is perhaps more realistic. Undoubtedly, as the soil solution moves down the soil column, reaction with the exchange surfaces of the colloids occur, which may change to some extent the solution composition. This will also result in the displaced soil solution being an average of the numerous equilibria which exist throughout the soil. However, according to Howard and Adams (1965) if plant growth in nutrient solutions simulating the displaced soil solution and plant growth in soil are the same, then a good estimation of the soil solution has been obtained.

CHARACTERIZATION OF SOILS

I - MATERIALS AND METHODS

Bulk samples were obtained of the Ap and Bnt or Bt horizons of seven Solonetzic soils of Alberta. Soils were sampled to represent the three Great Groups (Solonetz, Solodized Solonetz and Solod) of the Solonetzic Order. In all cases, soils of the same sub-group were sampled along adjacent, naturally occurring, Solonetz to Solod sequences (Table 1). All samples were air dried then passed through a 2mm sieve.

Soil moisture determinations at $-1/3$ bar and -15 bar were done using the pressure plate and pressure membrane extraction respectively (McKeague 1976). All soils had complete moisture characterization from oven dry (105°C) to saturation paste (see Appendix I). Electrical conductivity was determined using a conductivity bridge with a micro dipping type cell. A Beckman expanded scale pH meter was used for all pH determinations. Cations (Ca, Mg, Na and K) were determined by atomic absorption, using a Perkin-Elmer model 503 spectrophotometer.

Extractable cations were obtained using 1.0N ammonium acetate as outlined in Handbook 60 (USDA 1954). Gypsum requirement was determined by using a saturated gypsum

Table 1. Location, classification and parent material of soils under study[†]

<u>Location</u>	<u>Legal Location</u>	<u>Type</u>	<u>Sub-Group[†]</u>	<u>Parent Material</u>
Vegreville	17-52-14-4	Duagh silt loam	Black Solonetz	Saline lacustrine
Chipman	17-54-18-4	Duagh silt loam	Black Solonetz	Shallow lacustrine
Vegreville	17-52-14-4	Malmo silt loam	Eluviated Black Chernozem	Saline lacustrine
Killam	15-44-14-4	Killam loam	Black Solodized Solonetz	Glacial till
Killam	15-44-14-4	Daysland loam	Black Solod	Glacial till
Coronation	25-36-11-4	Hemaruka loam	Brown Solodized Solonetz	Glacial till
Coronation	25-36-11-4	Halliday loam	Brown Solod	Glacial till

[†] sequences are: Duagh - Malmo; Killam - Daysland; Hemaruka - Halliday

[†] CDA 1976

solution (USDA 1954). Determination of pH was based on a 1:2 $\frac{1}{2}$ soil water mixture. Soluble cations were extracted by filtration of a saturation paste left to equilibrate for over 12 hours (McKeague 1976). Cation exchange capacity was determined using sodium acetate to saturate the soil colloids, followed by removal of any excess with isopropyl alcohol and subsequent exchange of sodium by ammonium acetate (McKeague 1976). Exchangeable acidity was determined using a barium chloride-triethanolamine procedure (McKeague 1976).

II - RESULTS AND DISCUSSION

In general, the soil analyses (Tables 2 and 3) show little variation from that provided by Bowser et al. (1962) and Cairns (1961). Most of the Ap horizons are slightly acidic and a slight increase in pH occurs from Solonetz to Solod soils. Average pH values for the B horizons show little variation between Great Groups. Electrical conductivity consistently decreases in both A and B horizons along the Solonetz to Solod sequence, indicative of the desalinization by increased leaching and reduced influence of the saline groundwater on the soil solum.

Sodium decreases along the Solonetz to Solod sequence; which accounts for the earlier mentioned decrease in electrical conductivity (Tables 2 and 3). Reduced sodium

Table 2. Chemical characteristics of Black Solonetz and Black Solodized Solonetz and Brown Solodized Solonetz soils under study

Soil Series	Depth (cm)	E.C. mmhos/cm	pH	Soluble Cations meq/l			SAR	SSP ⁺	Ca [†] %	Mg/Ca	Exchangeable Cations meq/100g				CEC meq/100g	GYPSUM Requirement meq/100g	ESP	Exch			
				Na	Ca	K					Na	Ca	Mg	K				EA [*]	Ca/Na	Mg/Na	
Duagh Ap (Chipman)	0-5	1.55	6.1	20.23	1.20	0.57	0.14	21.52	91.00	0.05	0.48	7.35	7.65	7.63	0.89	20.38	51.58	8.12	14.25	1.04	1.00
Duagh Bnt (Chipman)	5-15	2.49	6.8	33.51	1.29	1.89	0.10	26.59	91.00	0.04	1.47	8.39	7.10	9.96	0.68	11.88	46.06	11.60	18.21	0.85	1.40
Duagh Ap (Vegreville)	0-12	0.67	5.9	7.39	0.61	0.51	0.13	9.85	86.00	0.07	0.84	2.57	8.29	5.24	0.87	21.94	42.73	1.90	6.01	3.23	0.63
Duagh Bnt (Vegreville)	12-40	2.56	6.8	25.65	1.35	2.96	0.07	17.45	85.00	0.04	2.19	5.50	7.39	10.59	0.45	13.20	38.36	6.98	14.34	1.34	1.43
Killam Ap	0-10	0.35	5.4	2.85	0.83	0.57	0.69	3.39	58.00	0.17	0.69	0.57	7.08	3.24	1.29	19.80	31.05	0.92	1.83	12.42	0.46
Killam Bnt	10-45	2.36	7.3	32.64	0.80	2.72	0.41	24.54	89.00	0.02	3.40	5.18	3.10	8.10	0.90	9.73	25.47	4.60	20.34	0.60	2.61
Hemaruka Ap	0-11	0.44	5.6	5.44	0.71	0.62	0.13	6.72	79.00	0.10	0.87	0.72	3.78	2.68	0.48	17.82	25.04	0.56	2.87	5.26	0.71
Hemaruka Bnt	11-25	6.41	8.0	89.21	8.70	26.00	0.36	21.44	72.00	0.07	2.99	5.57	11.11	10.29	0.56	7.18	33.20	3.30	16.77	2.01	0.93

⁺ Soluble sodium percentage

[†] Soluble sodium percentage

[†] Ratio of calcium to total cations

* Exchangeable acidity

Table 3. Chemical characteristics of Eluviated Black, Black Solod and Brown Solod soils under study

Soil Series	Depth (cm)	E.C. mmhos/cm	pH	Soluble Cations meq/l			SAR	SSP ⁺	Ca ⁺ /Mg ⁺ TC	Mg/Ca	Exchangeable Cations meq/100g				CEC meq/100g	GYPSUM Requirement meq/100g	ESP	Exch			
				Na	Ca	Mg					K	Na	Ca	Mg				K	Na	Mg	
Malmo Ap	0-22	0.39	6.2	1.96	2.30	2.05	0.51	1.33	29.00	0.34	0.89	0.70	23.39	9.2	1.75	19.63	51.49	0	1.36	33.40	0.39
Malmo Bt	22-60	0.34	7.2	2.13	1.30	1.07	1.00	1.95	39.00	0.24	0.82	0.90	15.92	9.71	3.63	12.54	42.00	0	2.14	17.68	0.61
Daysland Ap	0-30	0.26	5.6	0.61	1.75	1.07	0.59	0.64	15.00	0.44	0.61	0.20	17.04	4.58	1.19	19.71	36.38	0	0.55	85.15	0.27
Daysland Bt	30-50	1.11	7.4	7.40	11.65	3.79	0.17	2.66	32.00	0.51	0.33	0.92	33.22	5.41	0.37	6.27	29.11	0	3.16	36.11	0.16
Halliday Ap	0-30	0.35	7.2	0.46	4.55	1.07	0.29	0.27	7.00	0.71	0.24	0.23	19.60	2.84	1.55	6.35	25.20	0	0.91	87.39	0.14
Halliday Bt	40-60	0.39	7.8	3.48	2.27	0.99	0.33	2.35	49.00	0.32	0.44	0.99	19.80	6.92	2.11	5.77	29.48	0	3.36	20.04	0.35
+ Soluble sodium percentage																					

+ Soluble sodium percentage

† Ratio of calcium to total cations

* Exchangeable acidity

levels are more clearly indicated by comparing the soluble sodium percentages and sodium adsorption ratio. An increase in calcium, to give narrow calcium to total cation ratios, occurs in the Solod A horizon. Magnesium concentrations increase slightly in all of the A and some of the B horizons of the solodic soils, this is offset by the greater increase of calcium. Increase in divalent cations is most likely the result of improved plant growth and subsequent recycling of ions from lower horizons.

In regards to the exchangeable cations (Tables 2 and 3) the most obvious fact shown by the data is the increase in the calcium to sodium ratio on the soil colloids from the Solonetz to Solod soils. This is further demonstrated by a similar decrease in the gypsum requirement, which indicates an imbalance of sodium to calcium if the calculated value is positive. The ratio of magnesium to calcium also decreases in both horizons, this was also observed by Cairns (1961). Both the above cases emphasize the greater calcium domination of the soil exchange complex along the Solonetz to Solod sequences. Actual levels of adsorbed magnesium show no consistent decrease from a Solonetz to a Solod soil. Increases of magnesium occurred in the A horizon of one Solod (i.e. Daysland). In general, magnesium does decrease in the B horizons of the Solod soils (i.e. Daysland and Halliday) in comparison to the Solonetz or shows

little change (i.e. Malmo). This overlapping of levels of exchangeable magnesium between Great Groups of the Solonchic Order and associated Chernozemic soils has been reported elsewhere (Bowser et al. 1962). In general, exchangeable acidity decreases slightly in the Solod soils over that of the Solonetz soils. A large decrease is seen in the Halliday soil over that of Hemaruka soil. Differences in exchangeable potassium were also inconclusive. Soils such as the Halliday and Duagh showed an increase over the adjacent Hemaruka and Malmo in both horizons, while the Daysland Solod showed a decrease over the adjacent Killam. In conclusion, the main difference on the exchange complex between Solonetz and Solod soils is the increase in calcium and decrease in sodium.

The correlation between sodium adsorption ratio (SAR) of the saturation extract and exchangeable sodium percentages (ESP) on the colloids agrees with that reported elsewhere (USDA 1954). This reflects the equilibrium between the soil exchange sites and the soil solution at saturation percentage. USDA (1954) gives a correlation coefficient of 0.92 between ESP and SAR, while the results in this study give a correlation coefficient of 0.94 (Appendix II).

DETERMINATION OF SOIL SOLUTION

I - MATERIALS AND METHODS

Soil solutions were obtained using the displacement technique as outlined by Adams (1971a). Certain modifications were as follows: plastic tubing 5.5 cms (I.D.) X 70cm was used as the displacing column; 0.15N CaCl_2 plus 4% KCNS was utilized as a displacing solution. Adams (1971a) used a saturated CaSO_4 solution but this was found unsuitable due to the relatively low solubility of the CaSO_4 and subsequent low electrolyte concentration for maintenance of water infiltration into Solonetzic soils. The addition of KCNS to the displacing solution provides a tracer; the presence of small amounts of CNS^- in the displaced solution will give a dark red colour when one drop of FeCl_3 is added.

Ethanol was also used as a displacing solution. Ceric ammonium nitrate dissolved in nitric acid was used as an indicator to detect alcohol in the displaced solution. Presence of alcohol is indicated by a change in the colour of the reagent from yellow to red.

The procedure for displacement of the soil solution is outlined as follows: 1500-2000g of air dried soil is wetted to a desired moisture percentage (usually half-way

between $-1/3$ and -15 bar) using an atomizer; the moist soil is mixed well and allowed to equilibrate for a few days after which it is packed into the plastic tubes. The packing procedure demands some practice, being dependent on moisture content, organic matter percentage and texture. The latter is a critical factor especially for soils of high silt content (Adams 1971a). For instance, the Bnt horizon of the Duagh silt loam from Chipman was not successfully displaced due to silting up and subsequent impeded water movement. The displacing solution is added to the top of the column and maintained to give a constant head of 3cm. Movement of the displacing solution down the column occurs at a steady and even rate, taking between 1 to 5 hours to complete displacement. At the bottom of the column a No.42 Whatman filter paper held in position by cheesecloth gauze is used to prevent escape of any soil particles. The displaced soil solution, in 5ml consecutive portions, was collected until presence of the displacing solution was indicated. The 5ml portions were analyzed to determine if electrical conductivity and calcium concentrations remained constant (Fig. 1).

Determination of sulphates was done utilizing a turbidimetric procedure using Hach Sulflaver IV Sulfate Reagent. Bicarbonates were determined by titrimetry, using 0.01N H_2SO_4 and titrating to a methyl orange endpoint (pH 4.0). Chloride determinations were done using the Mohr method (Pierce

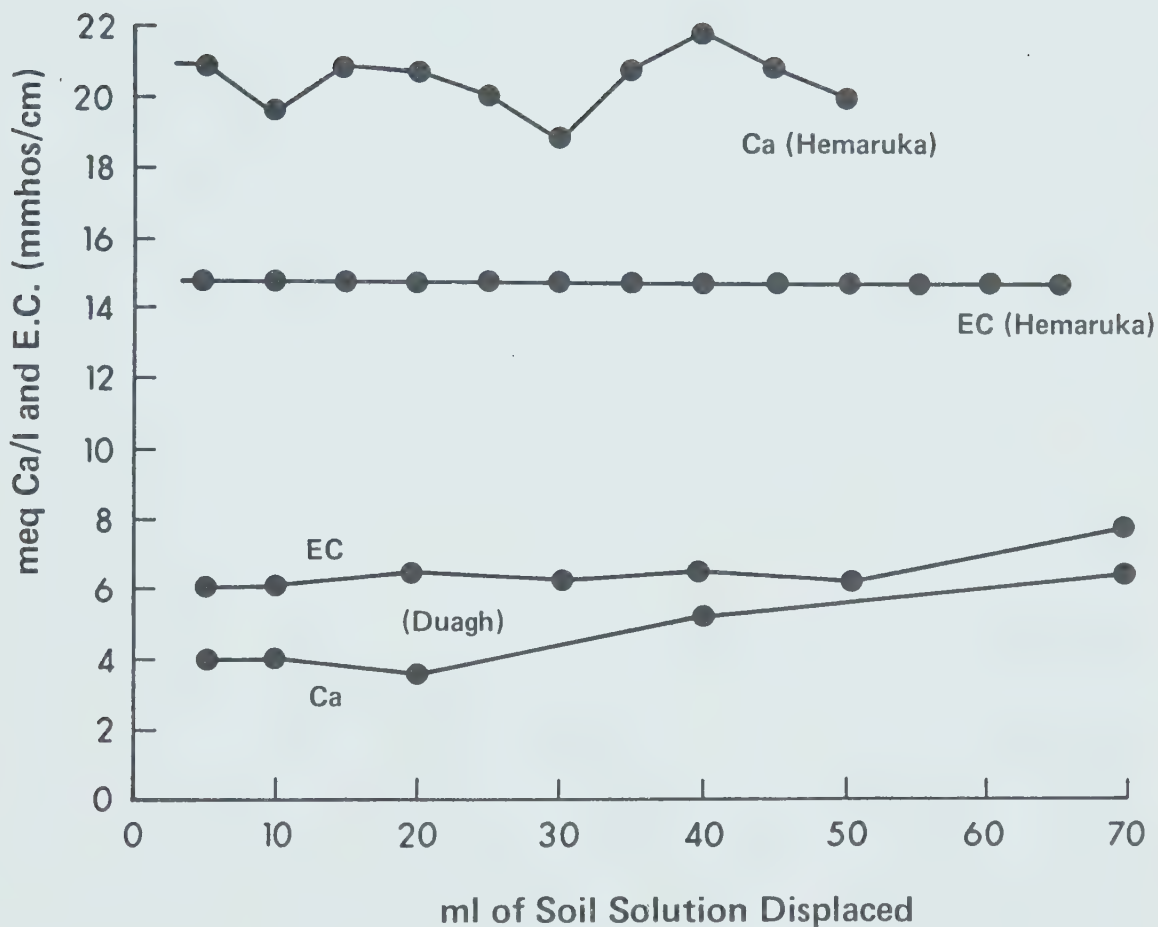


Figure 1. Electrical conductivity and calcium concentration of consecutive 5ml portions of a soil solution displaced at half available moisture percentage from a Hemaruka Bnt using ethanol and a Duagh Bnt using CaCl_2

and Haenisch 1956). Although chlorides are usually only found in low concentrations in Solonetzic soils of Western Canada, the use of chloride in the displacing solution, gave good reason for their determination to ensure no contamination had occurred.

II - RESULTS AND DISCUSSION

Analysis of the displaced soil solution (Fig. 1) showed relatively constant electrical conductivity and calcium content in the consecutive 5ml displaced portions. Small variations are expected due to variations within a soil and experimental error. Each portion had a similar composition and was free of any displacing solution. In the case of the CaCl_2 no CNS was indicated until 45ml of soil solution had been displaced from a Duagh Bnt horizon, although an increase in calcium began to take place after 20ml and the increase in electrical conductivity did not begin until 50ml had been displaced. This would indicate that approximately 30ml of homogenous soil solution could be displaced which represents 12% of the total soil moisture. In comparison, ethanol used on a Hemaruka Bnt horizon displaced up to 70ml free of ethanol, of constant electrical conductivity and calcium content (Fig 1). This represents 33% of the total soil moisture, although a higher efficiency could have been achieved if further fractions had been sampled. In this case, differences between the

two displacing solutions was probably a reflection of texture rather than efficiency. Other sources stress the importance of packing and the effect of texture in achieving maximum efficiency, which can reach 80% (Adams 1971a; Pearson 1971). A more involved analysis of the 5ml fractions displaced from a Hemaruka Bnt (Table 4) confirmed the relative constancy of the ionic constituents.

In general, the characteristics of the soil solutions (Tables 5 and 6) were similar to that reported elsewhere (Khan and Webster 1966). Sulphates were the dominant anion, while chloride and bicarbonate were in low amounts. The latter were high in the Halliday Bt and Hemaruka Bnt, although the Hemaruka Bnt had very high concentrations of sulphate. The dominant cation in the Solonetz and Solodized Solonetz soils, especially the Bnt horizon, was sodium. This was demonstrated by the high soluble sodium percentages and sodium adsorption ratio. In each case, an increase in calcium occurred in the A and B horizons along the Solonetz to Solod sequences. This was accompanied by a decrease in sodium and electrical conductivity. A similar decrease of magnesium also occurred in the B horizons. In essence, the chemical analysis of the soil solutions as far as proportions of constituents are concerned, are similar to those found in the saturation extract (Tables 2 and 3). However, increases in salinity as the soil moisture

Table 4. Composition of soil solutions (free of ethanol) displaced from a Hemaruka Bnt horizon at the half available moisture percentage using ethanol

	Consecutive 5ml Samples										s.d. [†]
	1	2	3	4	5	6	7	8	9	10	
E.C. mmhos/cm	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	
Ca (meq/l)	21.0	19.8	20.5	20.4	20.0	19.0	20.5	21.0	20.5	20.0	±0.6
Mg	79.0	70.0	75.7	75.7	73.2	69.1	72.0	79.0	79.0	74.0	±3.7
Na	208.7	195.6	213.0	204.3	200.0	195.6	200.0	208.7	195.6	195.6	±6.5
K	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Mg/Ca	3.76	3.53	3.69	3.71	3.66	3.64	3.51	3.76	3.85	3.70	±0.10
Ca/Tc ⁺ x 102	6.79	6.92	6.62	6.78	6.81	6.68	6.99	6.79	6.93	6.89	±0.11

+ Ratio of Calcium to Total Cations

† Standard deviation

Table 5. Chemical composition of soil solution from soils under study displaced at half available moisture percentage using 0.15N CaCl₂

Soil Series	pH	E.C. mmhos/ cm	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	SAR	SSP	Ca/ TC ⁺	Mg/ Ca
Solonetz and Solodized Solonetz Soils													
Duagh Ap (Vegreville)	5.6	1.31	0.80	0.90	13.03	0.28	0.57	14.30	0.10	14.2	86.00	0.05	1.16
Bnt	6.6	6.24	4.87	8.26	63.04	0.15	1.49	77.40	0.10	24.6	82.60	0.06	1.70
Killam Ap	5.7	1.39	3.85	2.60	8.60	1.66	0.41	15.50	0.15	4.8	51.00	0.23	0.68
Bnt	6.8	8.68	5.83	22.22	107.71	1.56	1.65	130.20	0.30	28.8	78.00	0.04	3.81
HemaruKa Ap	6.9	1.22	2.87	1.70	12.39	0.19	0.28	16.20	0.25	8.2	72.00	0.17	0.59
Bnt	7.7	15.08	19.69	68.85	199.09	0.69	10.03	265.93	0.20	32.4	69.00	0.07	3.50
Solod Soils													
Malmo [†] Ap	6.0	1.31	5.69	4.26	4.38	0.97	0.37	14.30	0.30	1.9	28.60	0.37	0.75
Bt	6.2	0.82	3.07	1.78	3.34	1.72	0.55	8.62	0.25	2.1	33.70	0.31	0.58
Daysland Ap	5.7	1.11	6.32	3.21	1.38	1.15	0.37	11.90	0.10	0.6	11.40	0.52	0.51
Bt	6.6	2.25	17.67	5.98	10.66	0.24	3.80	29.14	0.10	3.1	30.80	0.51	0.34
Halliday Ap	6.6	0.82	7.68	1.70	1.04	0.51	4.39	5.80	0.15	0.5	9.50	0.70	0.22
Bt	7.8	0.82	4.28	1.51	5.66	0.41	6.95	5.23	0.15	3.3	47.70	0.36	0.35

+ Ratio of Calcium to total cations

† Eluviated Chernozem

Table 6. Chemical composition of soil solution from soils under study displaced at half available moisture percentage using ethanol

Soil Series	pH	E.C. mmhos/ cm	meq/l							Cl	SAR	SSP	Ca/ ⁺ TC	Mg/ Ca
			Ca	Mg	Na	K	HCO ₃	SO ₄						
Solonetz and Solodized Solonetz Soils														
Duagh Ap (Chipman)	5.8	4.90	6.95	9.88	76.08	0.46	3.99	93.99	0.48	26.2	81.50	0.07	1.42	
Killam Ap	5.7	1.86	6.60	4.61	10.65	1.19	0.50	18.78	0.20	4.5	46.20	0.29	0.70	
Bnt	6.8	7.98	7.76	25.51	143.48	1.07	1.22	167.83	0.28	35.2	80.70	0.04	3.33	
Hemaruka Ap	6.9	1.20	3.32	1.81	9.77	0.16	0.55	14.77	0.24	6.1	82.30	0.22	0.55	
Bnt	7.7	14.70	20.29	73.80	202.90	0.54	14.40	271.75	0.12	29.6	68.00	0.07	3.64	
Solod Soils														
Malmö† Ap	6.0	1.26	7.52	8.23	3.52	0.69	1.60	18.24	0.26	1.4	17.63	0.38	1.09	
Bt	6.2	0.70	4.02	2.18	3.30	1.23	0.83	9.18	0.12	1.9	30.75	0.37	0.54	
Daysland														
Ap	5.7	0.98	8.22	4.20	1.54	1.05	0.55	14.77	0.12	0.6	10.30	0.55	0.51	
Bt	6.6	2.45	19.35	11.10	12.60	0.21	2.94	37.19	0.10	3.2	29.12	0.45	0.38	
Halliday														
Ap	6.6	0.84	11.65	2.43	1.19	0.51	5.37	10.31	0.16	0.4	7.50	0.74	0.21	
Bt	7.8	0.77	5.82	2.05	5.87	0.37	8.97	5.16	0.10	3.0	41.60	0.41	0.35	

+ Ratio of Calcium to total cations

† Eluviated Chernozem

decreases (from saturation paste to half available moisture) will cause some changes as described below. Certainly, the displaced soil solution gives a more accurate picture of the ionic environment surrounding plant roots under field moisture conditions, than that derived from saturation paste extracts.

The overall changes taking place are better expressed by the magnesium to calcium (Mg/Ca) and calcium to total cation ratios (Ca/TC). All the Ap horizons have a Mg/Ca ratio of one or less, except the Ap of the Solonetz soil. This would tend to put the Ap horizons of Solonetz and Bnt horizons of Solonetz and Solodized Solonetz soils in an unfavourable nutritional position for plant growth, especially in the light of past research (Lyle and Adams 1971; Mostafa and Ulrich 1976; Trelease and Trelease 1931). A similar trend can be observed with the Ca/TC ratio; again past research indicates a calcium limitation occurs when calcium falls below 10% of the total cations (Adams 1971a; Howard and Adams 1965; Khasawneh 1971; Lyle and Adams 1971).

Interesting relationships occur, in concentrations and ratios of ions, over the available moisture range in the B horizons of Solonetz and Solodized Solonetz soils (Tables 5, 6 and 7). Electrical conductivity (Fig. 2) is shown to increase as moisture decreases; similar results were obtained by Khan and Webster (1966). The increase in electrical conductivity followed a linear relationship, being

Table 7. Chemical composition of soil solution of two soils displaced at -1/3 bar or -15 bar moisture percentage using 0.15N CaCl_2

Soil Type	pH	E.C. mmhos/ Cm	meq/l					Cl	SAR	SSP	Ca ⁺ / TC	Mg/ Ca
			Ca	Mg	Na	K	HCO ₃					
Hemaruka												
Ap (-15bar)	6.4	1.71	3.90	2.96	14.14	0.24	0.43	9.99	2.00	7.64	67.00	0.18 0.76
Bnt	8.6	18.26	22.30	80.66	230.64	0.79	9.54	317.96	1.00	32.17	69.00	0.07 3.62
Hemaruka												
Ap (-1/3bar)	6.1	1.18	2.25	1.26	10.43	0.17	0.34	9.20	0.50	7.90	74.00	0.16 0.56
Bnt	8.5	12.60	17.02	51.03	161.01	0.66	10.19	196.55	0.50	27.62	70.00	0.07 3.00
Killam												
Bnt (-1/3bar)	6.4	6.65	3.80	14.81	93.56	1.02	1.40	100.30	1.50	16.05	83.00	0.03 3.90
+ Ratio of calcium to total cations												

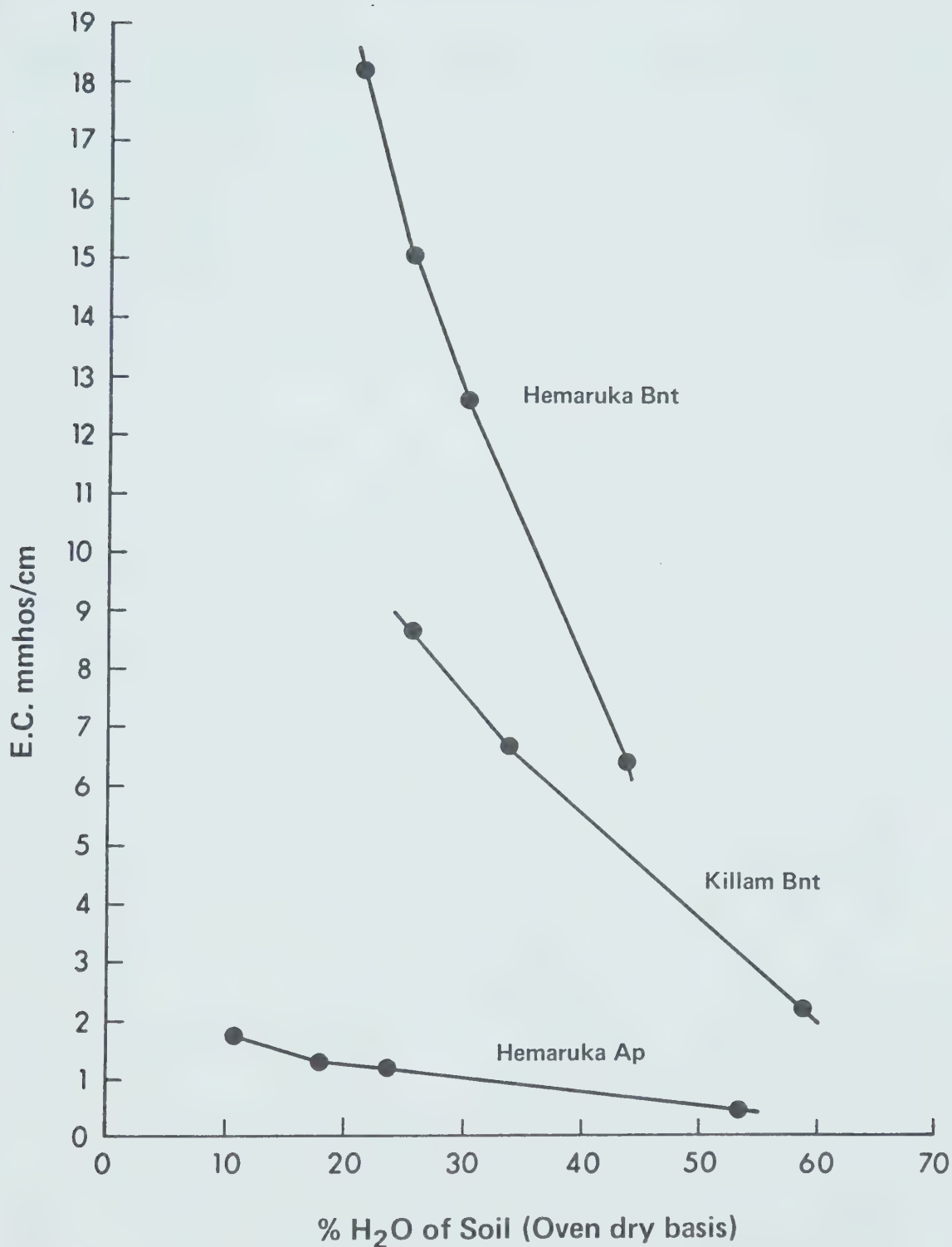


Figure 2. Change in electrical conductivity over the soil moisture range from saturation paste to near -15bar of some Solonetzic soils

specific for each soil. Changes in ion concentrations also occur with changes in moisture (Fig. 3). All ions tend to increase but at differing rates; for instance, magnesium increases faster than calcium to give a higher Mg/Ca ratio at half-available moisture than at saturation paste. However, the increase was not marked in the non-saline Solonchetsic soils (i.e. Duagh and Killam), but was significant in the saline Hemaruka soil. Similar increases in magnesium observed by Khan and Webster (1966) were the result of multiple equilibria between solid salt and colloid exchange phases. This may also be explained by the lower solubility of calcium sulphate when compared to magnesium sulphate which allows subsequent enrichment of magnesium as calcium is removed from solution. This will be very pronounced in saline soils, such as the Hemaruka, as the calcium level in a sulphate dominated system can rarely rise above 25 meq/l, unless the solution is highly saline.

The ratio of Ca/TC increased over the moisture range from saturation paste to half available moisture in the B horizon of the Duagh and Killam soils (Tables 2, 5, 6 and 7). This agrees with the dilution and valency law, which states that dilution of a soil system with water causes an increase in adsorption by the soil of higher valency ions (i.e. calcium), while lower valency ions (i.e. sodium) decrease (Moss 1963). In the case of the Hemaruka Bnt hor-

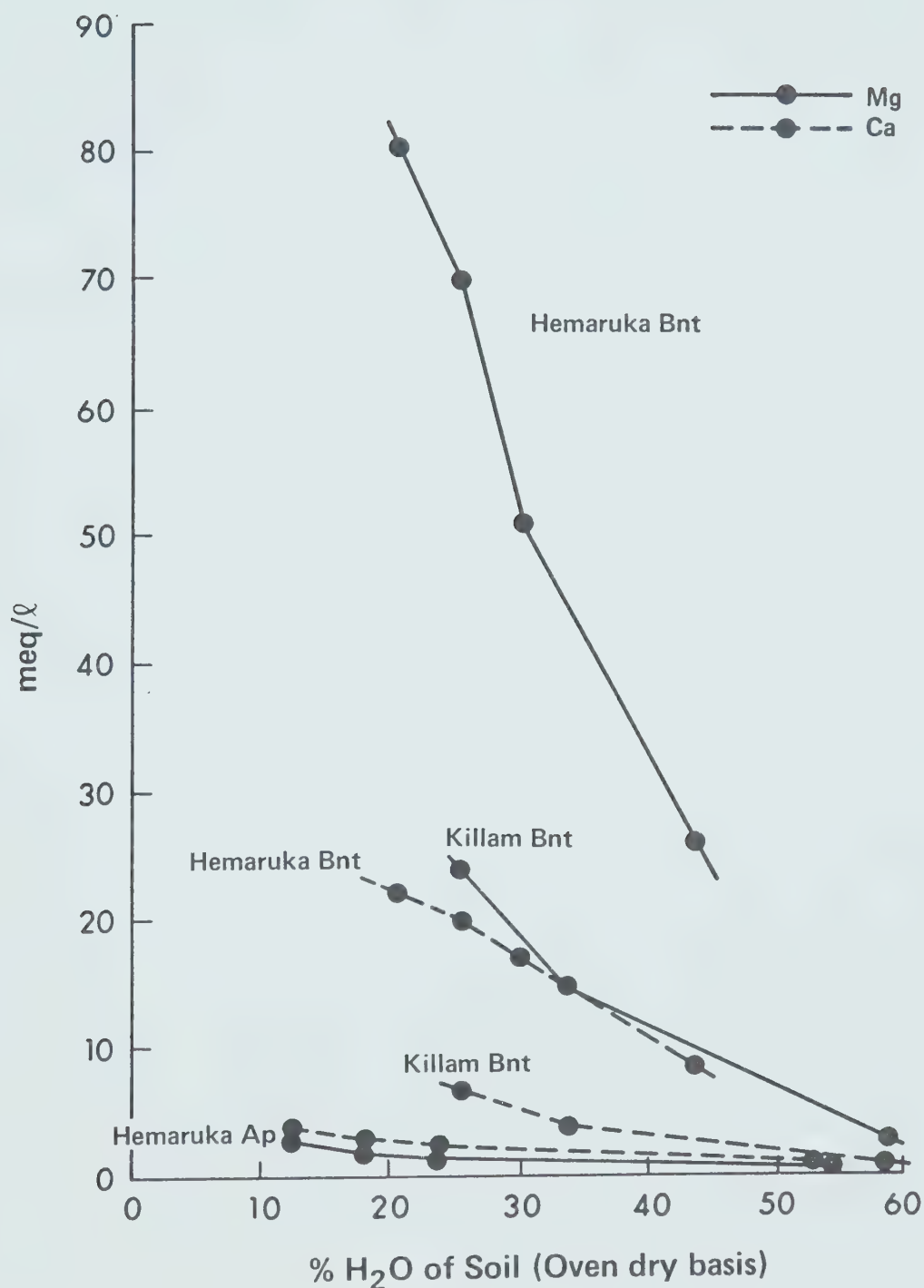


Figure 3. Changes in the concentration of magnesium and calcium in milli-equivalents per litre over the soil moisture range from saturation paste to near -15 bar of some Solonetzic soils

izon a constant ratio of Ca/TC is found over the range from saturation paste to near -15 bar moisture percentage (Tables 2, 5, 6 and 7). This is explained by the relatively large increase of magnesium concentration, in comparison to calcium, as the soil moisture decreases.

These results confirm the conclusions of Adams (1971a) and Pearson (1971) that attempts to relate the composition of soil extracts to that of the available moisture range, has not been entirely satisfactory. However, saturation paste extracts do give some indication of the expected ion composition at available moisture ranges, especially if the salinity status of the soil is known.

The Ap horizons of the Solodized Solonetz and Solod soils show no nutritional limitations for plant growth according to their soil solution composition (Tables 5 and 6). The B horizons of the Solod soils also failed to show any limitation. The main nutritional limitations for plant growth would be in the B horizons of Solonetz and Solodized solonetz soils, where low levels of calcium and high levels of other ions especially sodium and magnesium would present a hostile environment to plant roots. Similar conditions may exist in many Ap horizons of Solonetz soils.

SOLUTION CULTURE STUDIES

I - MATERIALS AND METHODS

1. General

Barley seeds (Hordeum vulgare var Galt) were germinated in vermiculite and transplanted to the solution culture at the one leaf stage. All roots were washed with distilled water before introduction to the solution. Plastic containers (ID 27cm) were used, each containing 11 litres of solution. The containers were covered with waterproofed masonite lids to prevent light and dust contamination. Seedlings were suspended through holes in the lid, being supported and protected by foam rubber, 7 seedlings were grown in each container. All solutions were aerated.

Solution culture experiments were arranged in a randomized block design, in a growth room with three replicates per treatment. The environment was controlled as follows: 16 hours light provided by cool white fluorescent lamps to give 16000 lux and temperature maintained between 17-21°C. Other environmental parameters, such as relative humidity and carbon dioxide content of the air, were not controlled.

The solution composition was based on a modification

of that prepared by Hoagland and Snyder (1933) and given in the appendix (III). To achieve desired ratios and concentrations of magnesium or calcium, additions of calcium nitrate, calcium sulphate and magnesium sulphate were used. Desired sodium and salinity levels were established by use of sodium sulphate. To achieve a measure of pH stability a combination of nitrate and ammonium forms of nitrogen was used. The ratio between nitrate and ammonium was maintained between 4-6.5:1 which is within the range reported by Hewitt and Smith (1975). The ammonium was added as ammonium phosphate, monobasic which replaced the potassium phosphate in the original base solution of Hoagland and Snyder (1933). Other changes were: the addition of sodium bicarbonate, to simulate bicarbonate levels found in soil solutions of Solonetzic soils; and the use of sodium nitrate to provide a constant nitrate level when calcium nitrate was low. Potassium levels were kept high in experiments I, II and III to prevent any potassium limitation for plant growth. In experiments IV and V potassium levels were reduced to that found in soil solutions of Solonetzic soils at half available moisture range. A constant level of anions (SO_4 , HCO_3 and NO_3) were maintained between treatments, so that, only the cation ratios and concentrations were a factor in affecting plant growth.

A complete micronutrient supplement was added to all solutions. The supplement (Appendix IV) covers all known

essential elements for higher plants (Hewitt and Smith 1975). Iron was added as an EDTA iron complex (to give 5ppm of Fe) derived from disodium EDTA and ferrous sulphate (Steiner and van Winden 1970). The pH of the solution was maintained at 5.5 by additions of sulphuric acid or sodium hydroxide. Solutions were changed once a week and distilled water added to maintain volume when necessary.

Barley seedlings were grown in solution for three weeks (experiments IV and V) or four weeks (experiments I, II and III). At harvest the roots and shoots were separated, weighed washed and dried at 70°C for three days, after which the samples were weighed then ground using a Wiley Mill. Dry ashing was done according to the procedure of Walsh (1971) and cations determined by atomic absorption.

The choice of barley for use in the solution studies was based on several factors. Barley can withstand fairly high salinity levels which are found in the soil solutions of Solonetz and Solodized solonetz soils. According to the USDA (1954) a 50 percent decrease in yield of barley occurs when the electrical conductivity (E.C) of the saturation extract reaches 16 (mmhos/cm). Also, barley is a commonly grown cereal and has been used extensively in research on salinity. Furthermore, the results from growth of barley at various ion concentrations and ratios may be generalised to include other cereals and crop species.

In each experiment the solutions before being changed were analysed to determine if any ions had substantially decreased. Little change was detected in concentration of any of the major constituents. Therefore, due to the short time which the plants were grown, changing solutions weekly was considered adequate to maintain a fairly constant ionic environment.

2. Specific experiments

Five different experiments were conducted in solution culture to assess various factors pertaining to barley growth at different ionic concentrations and ratios. Experiment I (Table 8) compared the growth of barley over a magnesium to calcium ratio (Mg/Ca) range of 0.6-16.5 at a constant S.A.R (3.5), EC (2.1) and ionic strength ($\mu=0.037$). Sodium levels were constant in each treatment. The calcium to total cation ratio (Ca/TC) ranged from 0.02 to 0.24. Concentrations of sodium, magnesium, calcium, sulphate and bicarbonate were similar to those found in the soil solutions at the half available moisture percentage of Ap horizons of Solodized Solonetz and Solod soils (Tables 5 and 6). Each treatment had the same sulphate concentration so that the only difference between treatments was the Mg/Ca ratio and Ca/Tc ratio. The concept of constant ionic strength for each treatment was considered important, as the activity coefficient of a particular ion is the same in all solutions

Table 8. Nutrient solution composition and related data for Experiment 1

	Treatment				
	1	2	3 meq/l	4	5
Na	8.0	8.0	8.0	8.0	8.0
K	6.0	6.0	6.0	6.0	6.0
NH ₄	2.0	2.0	2.0	2.0	2.0
Mg	4.0	6.0	7.5	8.5	9.9
Ca	6.5	4.5	3.0	2.0	0.6
NO ₃	12.5	12.5	12.5	12.5	12.5
HCO ₃	1.6	1.6	1.6	1.6	1.6
SO ₄	10.4	10.4	10.4	10.4	10.4
H ₂ PO ₄	2.0	2.0	2.0	2.0	2.0
E.C	2.1	2.1	2.1	2.1	2.1
Mg/Ca	0.6	1.3	2.5	4.2	16.5
Ca/TC	0.24	0.17	0.11	0.07	0.02
μ	0.037M	0.037	0.037	0.038	0.037
SAR	3.49	3.49	3.49	3.49	3.49

of the same ionic strength (Adams 1971b). A constant sodium adsorption ratio (SAR) was used; as the formula for SAR ($\text{Na} / \sqrt{\text{Ca} + \text{Mg} / 2}$ in meq/l) allows a constant sodium level with various concomitant Mg/Ca ratios. SAR is also an important parameter for Solonetzic soils.

Experiment II (Table 9) had the same salinity level as experiment I and similar ionic strength. Magnesium levels were kept constant in each treatment and calcium levels varied to give an increasing Mg/Ca ratio. This was done to determine if decreased growth was due to magnesium levels alone or an increasing Mg/Ca ratio. Sodium concentrations were varied in each treatment to ensure constant E.C and ionic strength.

Experiment III (Table 10) was conducted at high salinity levels comparable to that found in some Ap horizons of Solonetz soils and Bnt horizons of Solonetz and Solodized Solonetz soils (Tables 5 and 6). A constant SAR (21.5) and EC (8.43) was maintained between treatments. The ratio of Mg/Ca and Ca/TC ranged from 0.75 -7.75 and 0.03-0.15 respectively.

Experiment IV (Table 11) had a high level of sodium (42-50meq/l) in each treatment. Potassium was reduced from those levels found in previous experiments (6meq/l) to a low concentration (0.8meq/l) in each treatment. Varying concentrations of calcium (1-5meq/l) were used between treat-

Table 9. Nutrient solution composition and related data for experiment II

	Treatments		
	1	2 meq/l	3
Na	1.5	5.75	7.2
K	6.0	6.0	6.0
NH ₄	2.0	2.0	2.0
Mg	8.5	8.5	8.5
Ca	8.5	4.25	2.8
NO ₃	12.5	12.5	12.5
HCO ₃	1.6	1.6	1.6
SO ₄	10.4	10.4	10.4
H ₂ PO ₄	2.0	2.0	2.0
EC	2.1	2.1	2.1
Mg/Ca	1.0	2.0	3.0
Ca/TC	0.32	0.16	0.11
μ	0.040M	0.038	0.037

Table 11: Nutrient solution composition and related data for experiment IV

	Treatments				
	1	2	3	4	5
	meq/l				
Na	50.0	49.0	48.0	46.0	42.0
K	0.8	0.8	0.8	0.8	0.8
NH ₄	2.0	2.0	2.0	2.0	2.0
Mg	1.0	1.5	2.0	3.0	5.0
Ca	1.0	1.5	2.0	3.0	5.0
NO ₃	8.0	8.0	8.0	8.0	8.0
HCO ₃	2.0	2.0	2.0	2.0	2.0
SO ₄	42.8	42.8	42.8	42.8	42.8
H ₂ PO ₄	2.0	2.0	2.0	2.0	2.0
EC	3.7	3.7	3.7	3.7	3.7
Mg/Ca	1.0	1.0	1.0	1.0	1.0
Ca/TC	0.018	0.036	0.045	0.055	0.090
μ	0.076	0.077	0.077	0.078	0.080

ments. The Mg/Ca ratio was kept constant at 1.0, while the Ca/TC ratio ranged from 0.02 to 0.09. By keeping high sodium and low potassium constant, the effect of calcium levels can be observed on growth and also the ability to maintain adequate potassium uptake against sodium competition (Pitman 1975). Again, concentrations of ions reflect those found in the soil solutions of Solonetzic soils. The increase of calcium was followed by concomitant increases in magnesium to maintain a Mg/Ca ratio which from past research is not considered limiting (Lyle and Adams 1971; Trelease and Trelease 1931).

Experiment V (Table 12) was the same as experiment IV, except the Mg/Ca ratio was lowered to 0.5. This was done to further ensure that the Mg/Ca ratio was not a limiting factor. In general, the aim of experiments IV and V was to examine the relationship between Ca/TC ratio and Mg/Ca ratio on yield and the effect of these ratios on potassium uptake under sodium competition. Much of the past work has concentrated on sodium and potassium relationships (Heimann and Ratner 1962) and neglected the role of divalent ions in modifying this relationship (Elzam 1971; Pitman 1975).

Table 12. Nutrient solution composition and related data for experiment V

	Treatments			
	1	2	3	4
	meq/l			
Na	50.5	49.0	47.5	44.5
K	0.8	0.8	0.8	0.8
NH ₄	2.0	2.0	2.0	2.0
Mg	0.5	1.0	1.5	2.5
Ca	1.0	2.0	3.0	5.0
NO ₃	8.0	8.0	8.0	8.0
HCO ₃	2.0	2.0	2.0	2.0
SO ₄	42.8	42.8	42.8	42.8
H ₂ PO ₄	2.0	2.0	2.0	2.0
EC	3.7	3.7	3.7	3.7
Mg/Ca	0.5	0.5	0.5	0.5
Ca/TC	0.018	0.036	0.055	0.090
μ	0.077	0.078	0.078	0.080

II - RESULTS AND DISCUSSION

Growth and Yield of Barley

1. Experiment I (Mg/Ca 0.6-16.5; Ca/TC 0.02-0.24; EC 2.1 μ 0.037)

This experiment was conducted at low levels of electrical conductivity (EC) and ionic strength (μ) kept constant in every treatment (Table 8). All treatments showed similar growth for the first few days. After a week in solution treatments 4 and 5, which have Mg/Ca ratios of 4.2 and 16.5 and Ca/TC ratios of 0.07 and 0.02 respectively, began to show depressed growth followed by emergence of a shrivelled third leaf. This was followed by similar symptoms in treatment 3 (Mg/Ca ratio 2.5; Ca/TC ratio 0.11) until a progressive decrease in yield and increase in withering of the emerging leaf occurred from treatment 3 through to treatment 5. Treatments 1 and 2, which had Mg/Ca ratios of 0.6 and 1.3 and Ca/TC ratios of 0.24 and 0.17 respectively, showed normal growth with none of the above symptoms. Therefore barley growth was disrupted between a Mg/Ca ratio of 1.3 and 2.5, and a Ca/TC ratio of 0.11 and 0.17. Final dry weight yields show significant differences between some treatments (Table 13). Significant growth of tops follow closely that of a similar decline in root growth. However, growth of treatment 1 is not significantly different than that of treatment 3 which



1. Effect of increasing Mg/Ca ratio and decreasing Ca/Tc ratio on growth of barley in Experiment I, at constant SAR and EC

Table 13. Yield of tops and roots of barley from experiment I (g dry weight)

Treatments	1	2	3	4	5
Tops	10.01a ⁺	9.43ab	8.17ab	6.05b	0.54c
Roots	1.88a	1.82ab	1.60ab	1.15b	0.21c

+ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

had a Mg/Ca ratio of 2.5. This may indicate greater resistance to higher Mg/Ca ratios as the plant grows out of the seedling stage. Observations confirmed that the initial setback due to an adverse Mg/Ca ratio in barley seedlings was in some measure restored as the plant matured. Therefore at low salinity levels an adverse Mg/Ca ratio (i.e. >1.3) or low Ca/TC ratio (i.e. <0.17) will retard seedling growth, followed by a slow recovery to withstand a Mg/Ca or Ca/TC ratio of 2.5 and 0.11 respectively. This would indicate that the soil solutions of Ap horizons of Solodized Solonetz and Solod soils as well as the B horizons of the latter at field moisture levels, have no limitation to plant growth due to adverse ratios of calcium to other ions.

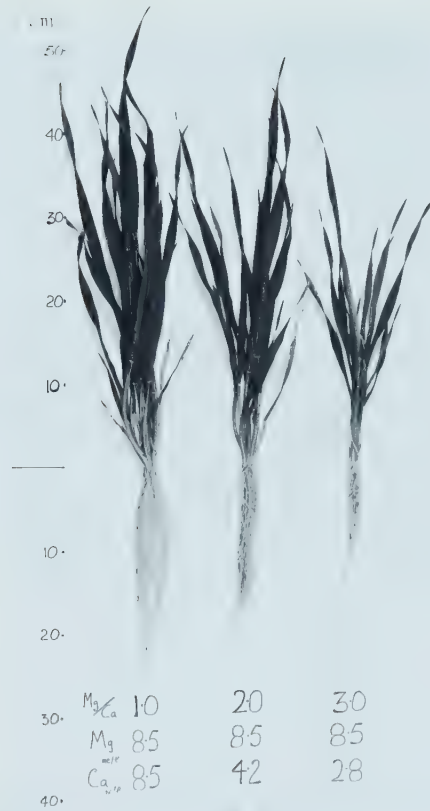
2. Experiment II (Mg/Ca 1.0-3.0; Ca/TC 0.11-0.32; EC 2.1; μ 0.037-0.040)

Experiment II had the same electrical conductivity (EC) and similar ionic strength (μ) in each treatment as that found in experiment I. Experiment II was different from experiment I in that a constant magnesium level was maintained in each treatment while a concomitant decrease in calcium allowed an increasing Mg/Ca ratio to occur (Table 9). This was done to determine if magnesium per se or Mg/Ca ratio was the limiting factor. After a week in solution a decline in height was observed from treatment 1

(Mg/Ca ratio 1.0; Ca/TC ratio 0.32) through to treatment 3 (Mg/Ca ratio 3.0; Ca/TC ratio 0.11). For instance, treatment 1 was at the five leaf stage while the tillers were at the three leaf stage. In comparison, treatment 3 was at the three leaf stage and tillers at the two leaf stage. Treatments 2 (Mg/Ca ratio 2.0; Ca/TC ratio 0.16) and 3 showed similar symptoms observed in experiment I, that is, withering of the emerging leaf. This usually occurred on the third or fourth leaf. Again, this effect declined to some extent as the plant matured. A significant decline in yield is seen between treatment 1 and 3 for both tops and roots (Table 14). This occurred at a constant magnesium level and would indicate the importance of the magnesium to calcium relationship. Another factor to take into consideration is that yield decline also followed a reduction in the Ca/TC ratio, as well as an increase in the Mg/Ca ratio. Further to this, the results establish the importance of calcium in ameliorating the adverse effects of magnesium and other ions on plant growth. Concentrations of magnesium per se do not seem to be a factor as all treatments had the same level.

3. Experiment III (Mg/Ca 0.75-7.75; Ca/TC 0.03-0.15; SAR 21.5; EC 8.43; μ 0.208)

Experiment III was similar to experiment I except that the salinity levels were raised much higher, so that, the



2. Effect of increasing Mg/Ca ratio and decreasing Ca/TC ratio on growth of barley in experiment II, at constant magnesium levels and EC

Table 14. Yields of tops and roots of barley from experiment II (g dry weight)

Treatment	1	2	3
Tops	12.23a ⁺	9.93ab	5.29b
Roots	2.59a	2.20ab	1.34b

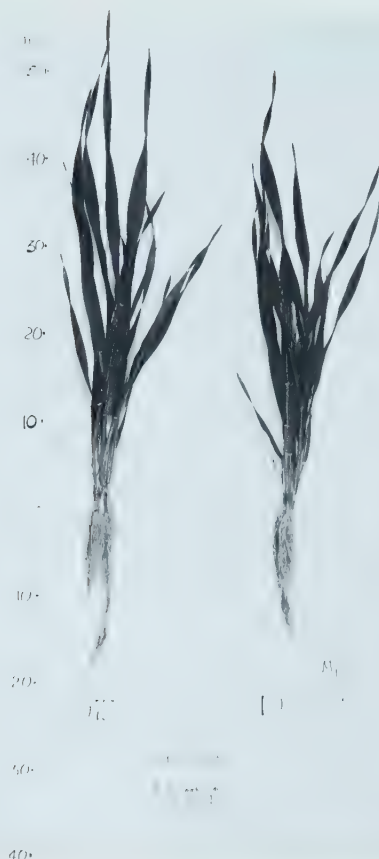
⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

effect of calcium to other ions could be assessed under a saline environment. Therefore increasing Mg/Ca ratios and decreasing Ca/TC ratios were used along with a high but constant salt level in each treatment (Table 10). After a week in solution all treatments showed withering of the emerging leaf, except treatments 1 and 2 which had Mg/Ca ratios of 0.75 and 1.06 and Ca/TC ratios of 0.15 and 0.13 respectively. Treatment 3 (Mg/Ca 1.33; Ca/TC 0.11) showed severe withering of the emerging leaf and reduction in yield (Table 15).

As indicated in previous experiments, increasing the Mg/Ca ratio caused a steady decline in growth of both tops and roots. The high salinity conditions created an osmotic effect which gave an added expected decrease in growth of all treatments when compared to experiments I and II. Final dry weights in treatments 1, 2 and 3 were not significantly different, even though treatment 3 showed some of the earlier mentioned symptoms (Table 15). Therefore, growth began to decline above a Mg/Ca ratio of 1.33 and below a Ca/TC ratio of 0.11. This observation is similar to earlier experiments.

4. Correlations between experiments I, II and III

The comparison between decline in relative yield and increasing Mg/Ca ratios is given in Figure 4. Relative yield is the dry weight yield in grams expressed as a percentage of the maximum yield. For instance, the highest



3. Effect of increasing Mg/Ca ratio and decreasing Ca/TC ratio on growth of barley at high and constant EC and SAR, in treatments 1 and 2 of experiment III

Table 15. Yields of tops and roots of barley from experiment III (g dry weight)

Treatment	1	2	3	4	5	6	7
Tops	6.84a ⁺	6.35a	5.67a	3.25b	1.41c	1.16c	0.39c
Roots	1.67a	1.56a	1.58a	1.07b	0.54c	0.45c	0.20c

+

Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

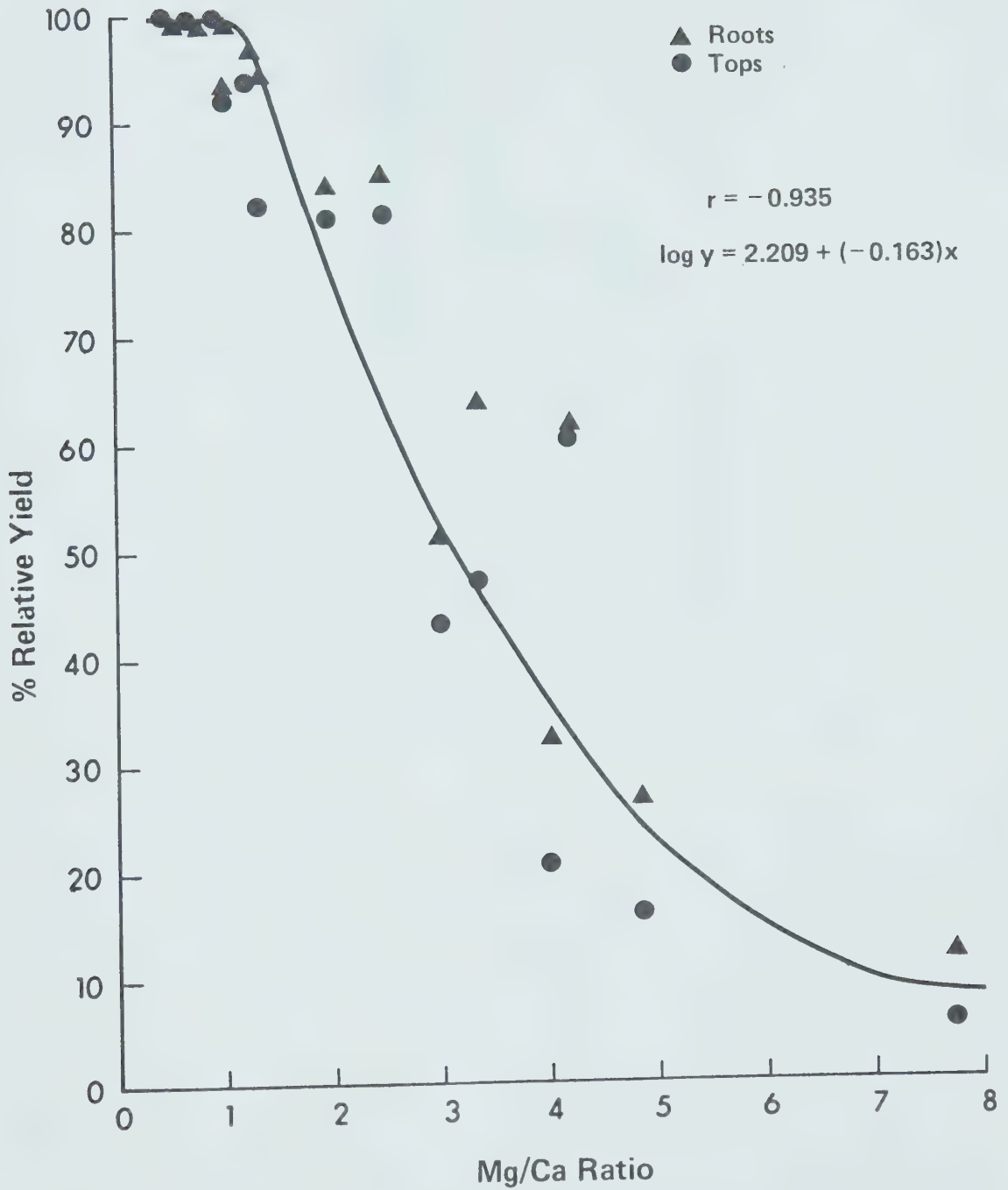


Figure 4. Correlation between Mg/Ca ratios in solution and relative yield of tops and roots of barley in experiments I, II and III



4. Effect of increasing Mg/Ca ratio and decreasing ca/TC ratio on growth of barley at high and constant EC and SAR in treatments 3, 4, 5, 6, and 7 of experiment III

yield in each experiment is given the maximum value of 100 percent and the other treatment yields expressed as a percentage of that value. A comparison of the three experiments show a decline in yield as the Mg/Ca ratio is increased. The correlation coefficient is given as -0.935 , while the curve is expressed as the antilog of $\log Y$ (Fig. 4).

In a similar fashion the correlation coefficient between percentage relative yield and Ca/TC ratio is given as 0.898 (Fig. 5). The interesting feature of both corre-

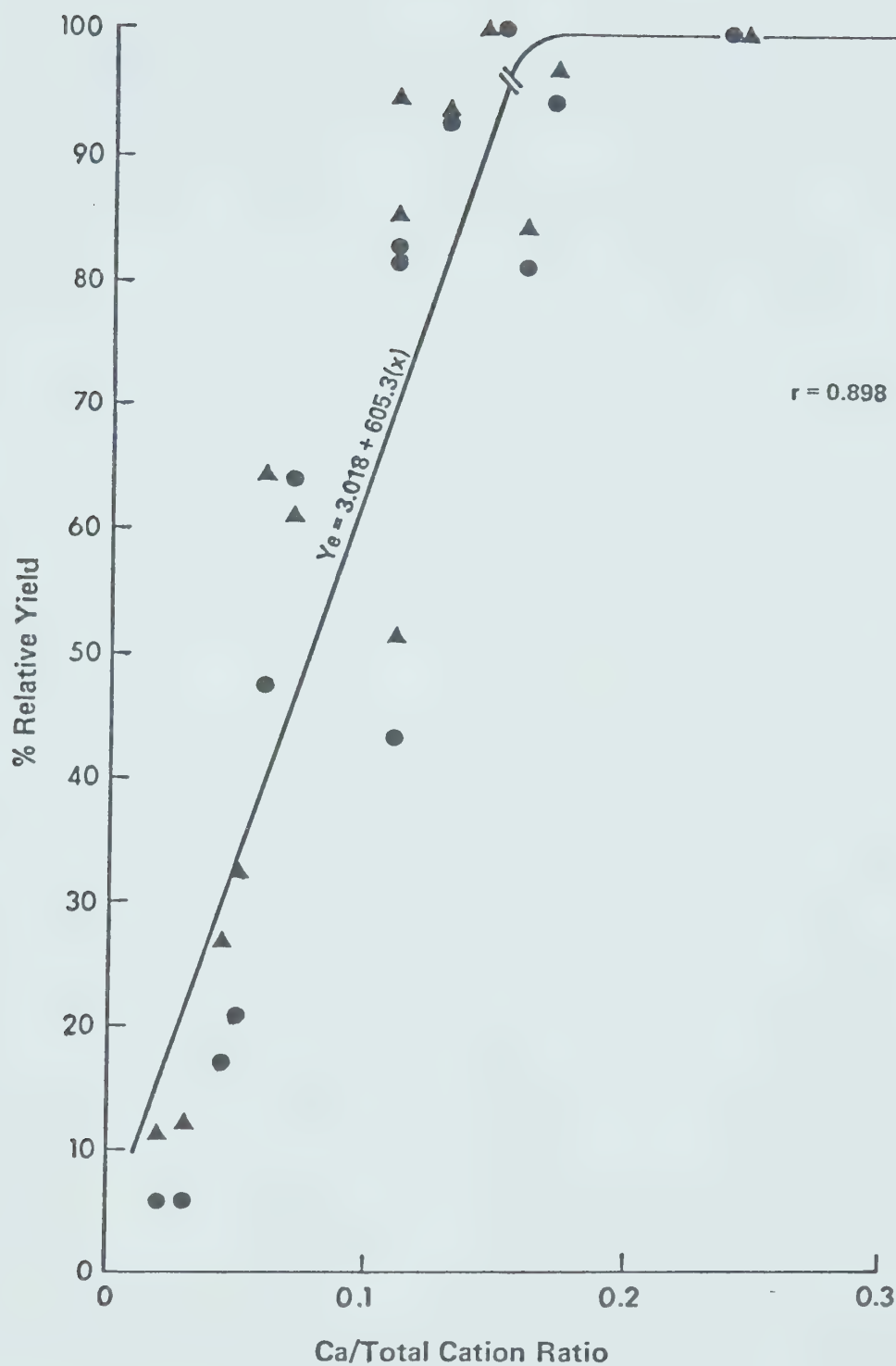


Figure 5. Correlation between calcium to total cation ratios in solution and relative yield of tops of barley in experiments I, II and III

lations is that the decline in yield is dependent on the ratio of calcium to other cations and not dependent on the concentration of calcium or magnesium per se. An example of this is treatment 3 in experiment I and treatment 3 in experiment III. Each treatment has the same Ca/TC ratio and similar decrease in relative yield, yet in experiment I 3.0 meq/l of calcium is used as compared to 15 meq/l of calcium in experiment III. Furthermore, these relationships are consistent regardless of ionic strength as seen in comparing experiments I and II (μ 0.038) with experiment III (μ 0.208).

Further comparisons of the data indicate that a Mg/Ca ratio of approximately 1.0 is needed to ensure optimum growth of barley (Fig. 4). This is a similar value to that observed by Lyle and Adams (1971) which give a value of 1.3. Trelease and Trelease (1931) indicate that no decrease in yield of wheat occurs if the Mg/Ca ratio is 1.0 or less. In the case of the Ca/TC ratio (Fig 5) about fifteen percent of the total cations need to be calcium to ensure optimum yield. This compares with other research by Howard and Adams (1965) who observed a critical Ca/TC ratio of 0.1-0.15 for optimum growth of primary cotton roots (Gossypium hirsutum), and Lyle and Adams (1971) who give a critical ratio of 0.10 for optimum elongation of loblolly pine (Pinus taeda L.) roots.

In experiments I, II and III the Mg/Ca ratio and Ca/TC ratio are in a sense a reciprocal of each other and both have similar correlation coefficients. The Ca/TC ratio takes into consideration the change in concentration of all other ions relative to calcium. Therefore, the Mg/Ca ratio is essentially a part of the Ca/TC ratio. Other research has concluded that the Mg/Ca ratio can better be expressed by the Ca/Tc ratio, and that the former is really only part of the latter (Khasawneh 1971). It is reasoned that the ion antagonistic effects on calcium are the result of the total cation concentration in solution and not restricted to the magnesium concentration. However, in the case of experiments I and II, especially the latter, magnesium would have a greater contribution towards ionic strength than monovalent cations. Furthermore, calcium and magnesium have similar ion activity coefficients, so that, the Mg/Ca ratio in molar concentration would be similar to the Mg/Ca ratio in molar activities (Lyle and Adams 1971). Therefore, taking the above into consideration, and the fact that high magnesium levels are found in some Solonchic soils, the Mg/Ca is still a useful parameter for assessing if calcium limitations exist in soil solutions.

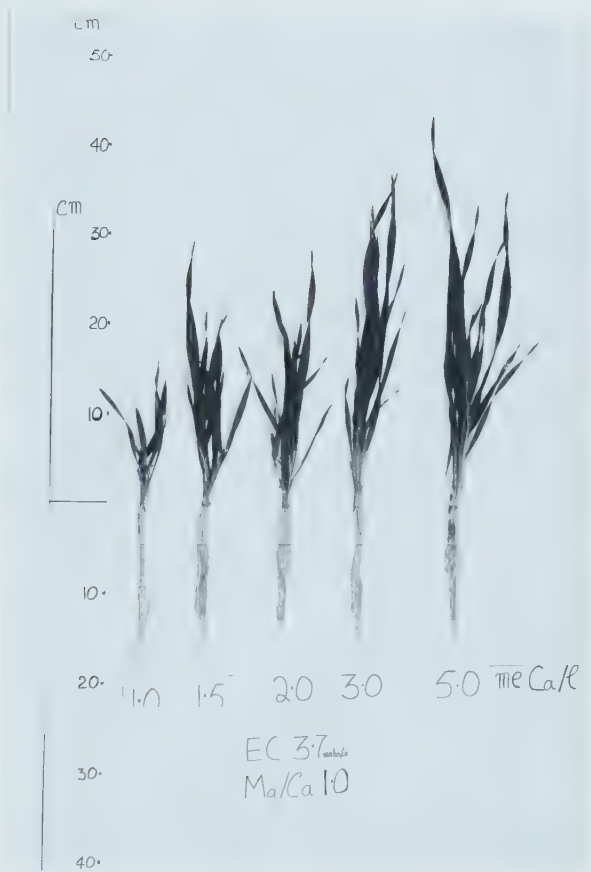
In conclusion, experiments I, II and III indicate that the Mg/Ca ratio and Ca/TC ratio are useful parameters for characterizing the soil solution, in regards to the cal-

cium regime, although the latter ratio is more versatile, as it is capable of evaluating the whole cation environment. Observations from soil solutions at field moisture levels (Tables 5 and 6) show adverse Mg/Ca and Ca/TC ratios exist in the Ap horizons of the Solonetz soil (i.e. Duagh) and Bnt horizons of Solonetz and Solodized Solonetz soils.

5. Experiments IV and V (Mg/Ca 1.0 and 0.5; Ca/TC 0.018-0.090; EC 3.7; μ 0.076-0.080)

Experiments IV and V had constant EC (mmhos/cm) in each treatment and fairly constant ionic strength (Tables 11 and 12). The Mg/Ca ratio was constant at 1.0 and 0.5, in each treatment of experiments IV and V respectively. The objective of these two experiments was to assess the effect of increasing Ca/TC ratios, keeping the Mg/Ca ratio constant, on growth of barley. At the same time, the potassium levels in each treatment were reduced to an average of those observed at half available moisture percent in soil solutions of Solonetzic soils (0.8 meq/l), in contrast to the high amount used in experiments I to III (6.0 meq/l). This was done to measure the effect of increasing Ca/TC ratio on potassium uptake, at fairly high levels of sodium.

In regards to experiment IV significant increases in yield are shown, as the Ca/TC ratio increases (Table 16). After one week of growth, treatments 1, 2 and 3 (Ca/TC ratios 0.018, 0.036 and 0.045 respectively) showed withering symptoms on the emerging third leaf. At the end of three



5. Effect of an increasing Ca/TC ratio on growth of barley in experiment IV

Table 16. Yields of tops and roots of barley from experiment IV (g dry weight)

Treatments	1	2	3	4	5
Tops	1.39e ⁺	2.09d	2.67c	3.35b	3.93a
Roots	0.48c	0.58b	0.67b	0.82ba	0.96a

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

weeks, the remaining treatments 4 and 5 (Ca/TC 0.055 and 0.090 respectively) also had some of the above symptoms. For instance, symptoms were observed on 100, 100, 95, 38 and 14 percent of plants in treatments 1, 2, 3, 4 and 5, respectively. Therefore, higher levels of calcium ($>5\text{meq/l}$ and Ca/TC 0.090) would be required to eliminate any of the observed symptoms and give further yield increases.

Experiment V gave similar results as experiment IV in regards to yield (Table 17) and withering of the emerging leaf. Symptoms were observed on 100, 76, 28 and 10 percent of plants in treatments 1, 2, 3 and 4 respectively. This corresponds to a Ca/TC ratio of 0.018, 0.036, 0.055 and 0.090 for treatments 1-4, respectively.

Both experiments IV and V indicate that optimum Mg/Ca ratios must also have adequate Ca/TC ratios to prevent yield decline. In this case, calcium concentration can be used to correlate with relative yield because both experiments IV and V have the same ionic strength. However, experiments with differing ionic strength (such as experiments I and III), as mentioned earlier, will give poor correlation to relative yield using only calcium concentration. This was also noted by Pearson (1971). Therefore, the utility of the Ca/TC ratio in predicting low calcium levels, even when the Mg/Ca ratio is optimum, is further demonstrated.

Table 17. Yields of tops and roots of barley from experiment V (g dry weight)

Treatments	1	2	3	4
Tops	0.86c ⁺	3.03b	3.18ba	4.22a
Roots	0.32d	0.77c	0.88b	1.18a

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

6. Calcium deficiency vs magnesium toxicity

In all experiments adverse Mg/Ca or Ca/TC ratios, produced withering of the emerging leaf. Another consistent symptom was a spiralling of the base of the withered leaf. Similar symptoms were observed by Trelease and Trelease (1931) in barley, corn, rye and wheat at the third leaf stage, when the Mg/Ca ratio exceeded 1.0. They concluded that the injury was mainly due to magnesium when magnesium concentration exceeds that of calcium. High magnesium in relation to calcium will result in rapid absorption of magnesium, which unless accompanied by sufficient calcium will exert toxic effects. Trelease and Trelease (1931) further observed that magnesium injuries could be inhibited by addition of strontium, therefore magnesium toxicity rather than calcium deficiency is envisioned. However, in solu-

tion culture strontium can replace calcium to some extent (Chapman 1966). Therefore, the evidence for magnesium toxicity may not be that conclusive. Mostafa and Ulrich (1976) found that magnesium induced calcium deficiency in sugarbeets at a Mg/Ca ratio of over 1.0. They concluded that magnesium interferes with calcium uptake. In this study, similar symptoms occurred at either adverse Mg/Ca or Ca/TC ratios, although the spiralling phenomenon was more pronounced in the former. It would seem as if the symptoms are due to calcium deficiency induced by high amounts of magnesium or other ions, even though calcium levels per se may not be nutritionally limiting. Therefore, ion antagonistic effects on calcium uptake coupled with an inadequate balance of calcium to other ions, to protect absorption processes, is envisioned as the cause for symptoms of calcium deficiency. In conclusion, the role of calcium in regulating the physiological effects of other ions on plant growth (Lund 1970; Wyn Jones and Lunt 1967; and Wallace et al. 1966) is evident at the concentrations and ratios of ions found in the soil solutions of Solonchalic soils.



6. Calcium deficiency in barley induced by low calcium and high amounts of other ions in solution

Plant Analyses

Plant analyses for sodium, potassium, magnesium and calcium for experiments I to V are given in Tables 18 to 22. The first observation is the close correlation between the Mg/Ca ratio of the solution (in meq/l) to that found in the barley leaves (in %). The calculated correlation coefficient using the total data was 0.979 (Fig 6). If both ratios are expressed on a milliequivalent basis then the same ratio approximately is found in both solution and leaves. This of course, is the end result of many intermediate pro-

Table 18. Plant analyses of tops and roots of barley in Experiment I

	Treatment				
	1	2	3	4	5
%	Tops				
Ca	0.52a ⁺	0.38b	0.28c	0.20d	0.17e
Mg	0.24b	0.32b	0.37b	0.41b	1.04a
Na	0.74b	0.76b	0.78b	0.78b	2.18a
K	4.45a	4.77a	5.04a	4.44a	3.56b
	Roots				
Ca	0.18a	0.16b	0.15b	0.10c	0.15b
Mg	0.11b	0.11b	0.15b	0.14b	0.34a
Na	0.41b	0.40b	0.52b	0.42b	0.67a
K	3.47a	3.30a	3.96a	3.56a	2.90b

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

Table 19. Plant analyses of tops and roots of barley in Experiment II

	Treatment		
	1	2	3
%	Tops		
Ca	0.51a ⁺	0.33b	0.20c
Mg	0.31a	0.32a	0.29a
Na	0.22c	0.52b	0.59a
K	4.73a	4.63b	3.47c
	Roots		
Ca	0.19a	0.12b	0.11b
Mg	0.13a	0.13a	0.13a
Na	2.30b	3.20a	3.80a
K	4.07a	3.27b	2.57c

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

Table 20. Plant analyses of tops and roots of barley in Experiment III

Treatment	%			
	Ca	Mg	Na	K
Tops				
1	0.33a ⁺	0.19d	2.70d	2.33a
2	0.28b	0.21d	2.90d	2.12b
3	0.22c	0.21d	2.50d	2.11b
4	0.17d	0.32c	3.40c	1.63c
5	0.15d	0.36bc	3.60c	1.28d
6	0.17d	0.41b	4.20b	1.31d
7	0.18d	0.77a	5.56a	1.08e
Roots				
1	0.21a	0.12c	2.00c	2.54a
2	0.18a	0.13c	2.00c	2.61a
3	0.15b	0.14bc	2.20b	2.41a
4	0.12b	0.15b	2.23b	2.62a
5	0.12b	0.18b	2.33b	2.25b
6	0.13b	0.18b	2.46b	2.27b
7	0.18a	0.35a	3.29a	1.99c

⁺ Values in the same column that have a letter in common are not significantly different ($P \leq 0.05$)

Table 21. Plant analyses of tops and roots of barley in Experiment IV

	Treatment				
	1	2	3	4	5
%	Tops				
Ca	0.17c ⁺	0.18c	0.22b	0.28a	0.30a
Mg	0.14b	0.16b	0.18ba	0.20a	0.21a
Na	4.07a	3.30b	2.90c	2.70c	2.23d
K	1.45e	1.83d	2.23c	2.57b	3.01a
	Roots				
Ca	0.14b	0.13b	0.14b	0.13b	0.17a
Mg	0.13a	0.12a	0.11a	0.13a	0.12a
Na	2.23a	1.93b	2.02b	1.61c	1.56c
K	2.07b	1.93b	2.10b	2.43a	2.45a

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

Table 22. Plant analyses of tops and roots of barley in Experiment V

	Treatment			
	1	2	3	4
%	Tops			
Ca	0.12c ⁺	0.18b	0.19b	0.29a
Mg	0.07c	0.11b	0.13b	0.15a
Na	5.63a	4.30b	3.53c	3.57c
K	0.90c	2.00b	2.07b	2.30a
	Roots			
Ca	0.11b	0.11b	0.12b	0.14a
Mg	0.09b	0.10b	0.12a	0.13a
Na	1.43a	1.39a	1.20b	1.26b
K	0.92c	1.93b	1.89b	2.01a

⁺ Values in the same row that have a letter in common are not significantly different ($P \leq 0.05$)

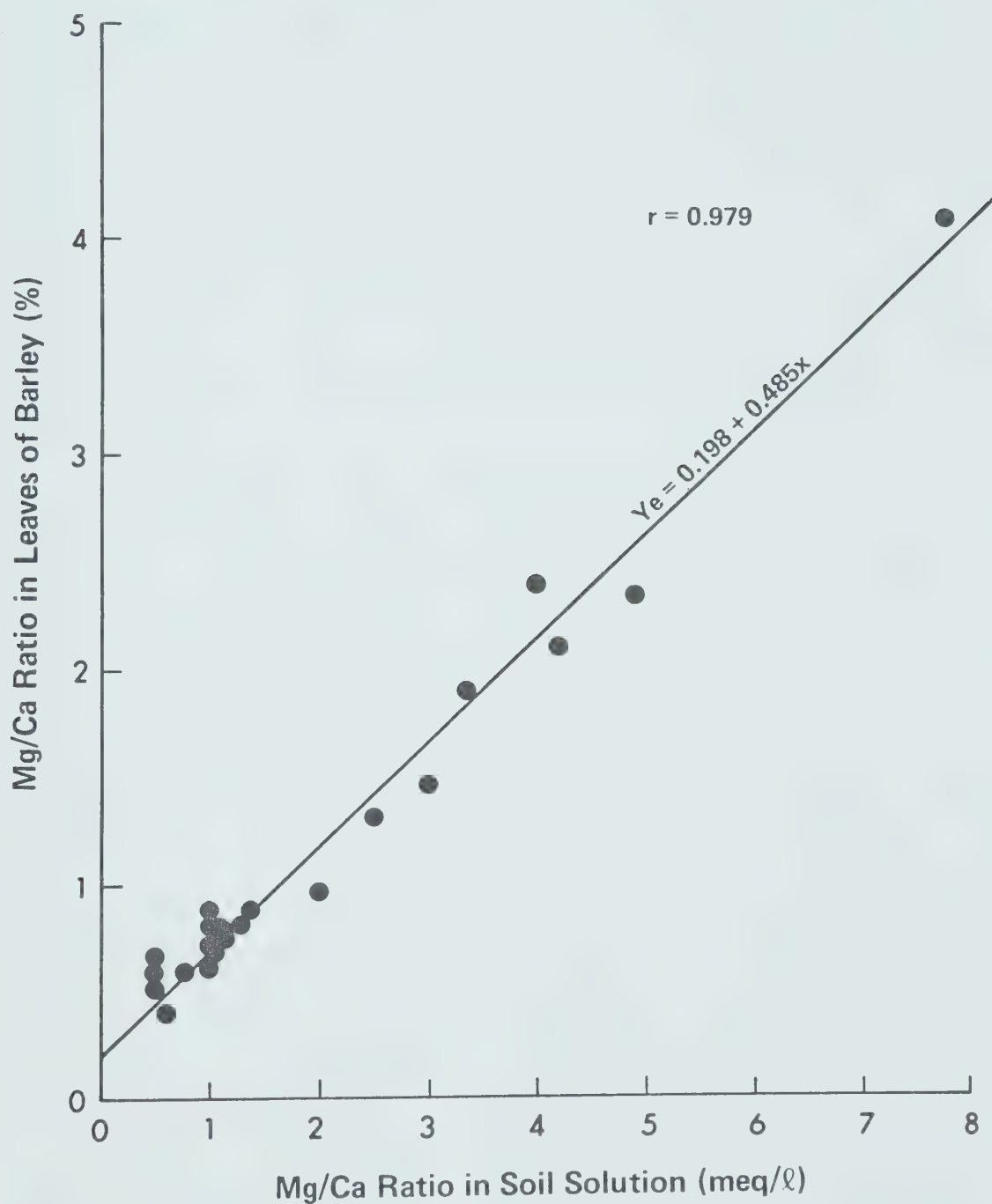


Figure 6. Correlation between the Mg/Ca ratio found in solution to that found in the leaves of barley (dry weight)

cesses in ion absorption and does not lend itself to speculation on rates of absorption of calcium and magnesium. Such factors as import and export of ions from leaves, growth of leaf, age, rate of transpiration, temperature as well as composition of the solution will regulate ion concentration in the leaf (Pitman 1975). However, the fact that adverse ratios of magnesium to calcium gave similar ratios in the leaves of barley after a few weeks of growth could provide an indirect way of assessing nutritional limitations.

Another important correlation is the percentage of calcium in the foliage and percentage of calcium of the total cations in solution, which gives a correlation coefficient of 0.931 (Fig. 7). Comparison of the concentrations of calcium in the various solutions used and the corresponding percentage of calcium in the foliage give little correlation. For instance, treatment 3 of experiments II and III have a similar percentage of calcium in the foliage and the same Ca/TC ratio in solution, but concentrations of calcium in solution are much different. According to Chapman (1966) a calcium percentage of less than 0.14 gave calcium deficiency symptoms in young wheat plants. In this study, calcium deficiency symptoms were observed on all plants when the calcium percentage fell below 0.22. This occurred at different and in most cases at relatively high concentrations of calcium but at the same ratio of calcium

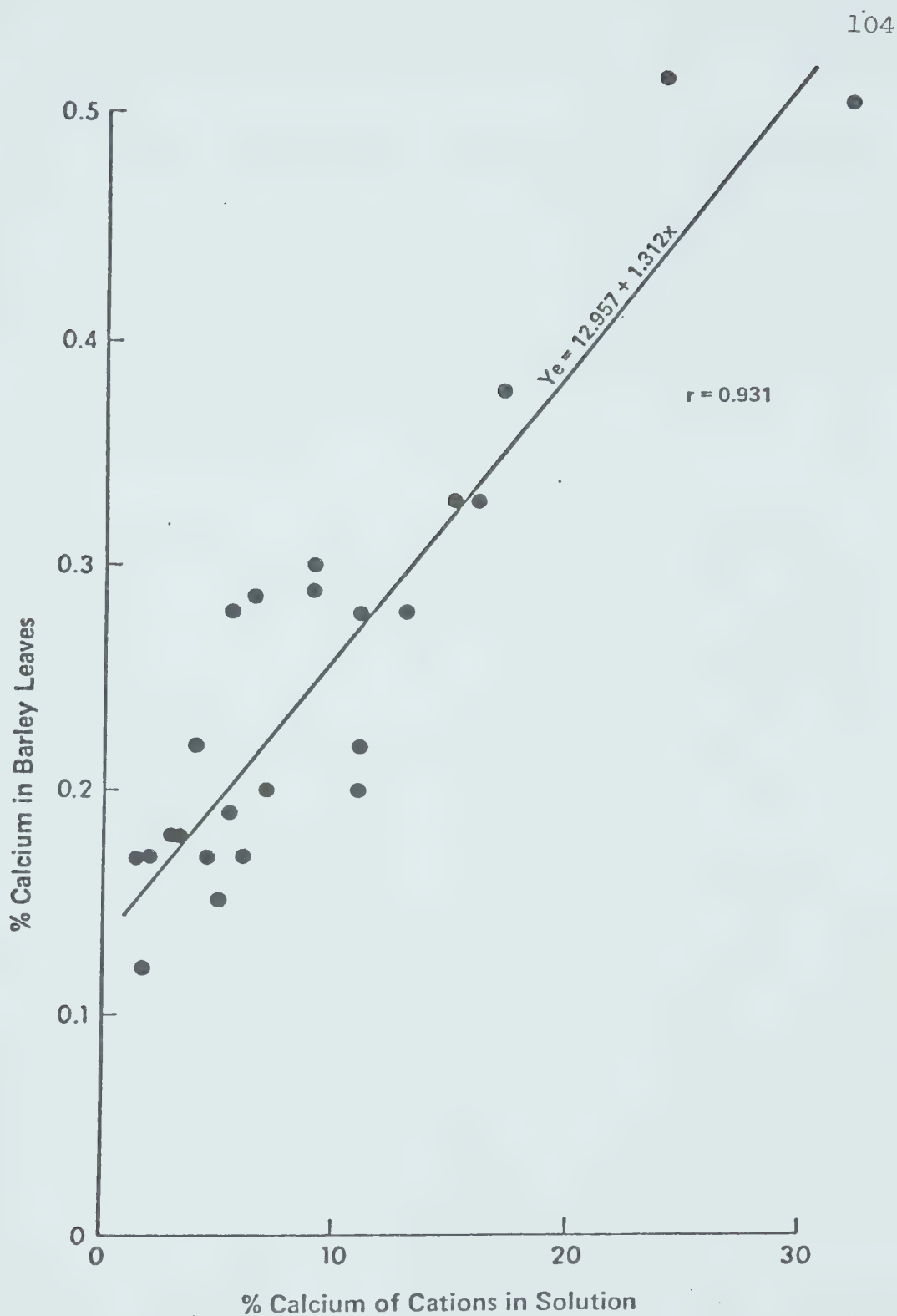


Figure 7. Correlation of percentage calcium in barley leaves with percentage calcium of cations in solution

to other cations. Therefore, the importance of the ratio of calcium to other ions in assessing calcium availability for plant growth is established. This also confirms the results of Lund (1970) and Wallace et al. (1966, 1968) in that the calcium requirement in solution for optimum plant growth is dependent on the concentration of other ions in solution.

In experiments I, III, IV and V, constant potassium and sodium concentration in solution at different calcium concentrations, allow the effect of calcium on selectivity of sodium and potassium uptake to be assessed. Other research has shown that the ability of plants to take up potassium selectively appears to depend on availability of divalent cations (Pitman 1975). Observations from experiments I, III, IV and V (Tables 18 - 22) indicate that sodium uptake significantly increases, while potassium uptake significantly decreases, as the Ca/TC ratio declines in the solution. Treatments which showed extreme calcium deficiency gave greater indication of the above phenomenon. This would indicate that calcium is an essential element in encouraging potassium selectivity and uptake in the presence of a competitive ion such as sodium. Therefore, the conclusions of Pitman (1975) should be expressed as the availability of calcium rather than divalent ions, as magnesium could not replace calcium in maintaining potassium selectivity. The

importance of calcium for potassium uptake is more pronounced in saline solutions. This can be seen in Fig. 8 where relatively saline solutions (experiments III and V) give much lower potassium to sodium ratios in the leaves, than non-saline solutions (experiment I), as the Ca/TC ratio decreases in solution, causing potassium to approach deficiency levels (0.70 - 1.50% dry weight basis) in the leaves. Therefore, competition between potassium and sodium for uptake into the plant cannot be completely understood from a basis of their concentration and ratio alone, as proposed by Heimann and Ratner (1962), nor by the concentration of divalent cations (Pitman 1975). The essential factor is to supply an adequate percentage of calcium in solution, this will depend of course on the level of salinity. Saline solutions found in some Solonetz A horizons and Solonetz and Solodized Solonetz B horizons will need a Ca/TC ratio in excess of 0.1 to maintain potassium levels over 2.0% in the leaves. Moreover, as long as adequate levels of calcium are present the potassium concentration in the soil solution can be low. This is demonstrated in experiment III (6.0meqK/l) and experiment V (0.8meqK/l). In regards to the latter experiment, potassium selectivity was maintained even at very low potassium concentrations, provided the Ca/TC ratio was not limiting. This is in agreement with the kinetics of potassium absorption as proposed

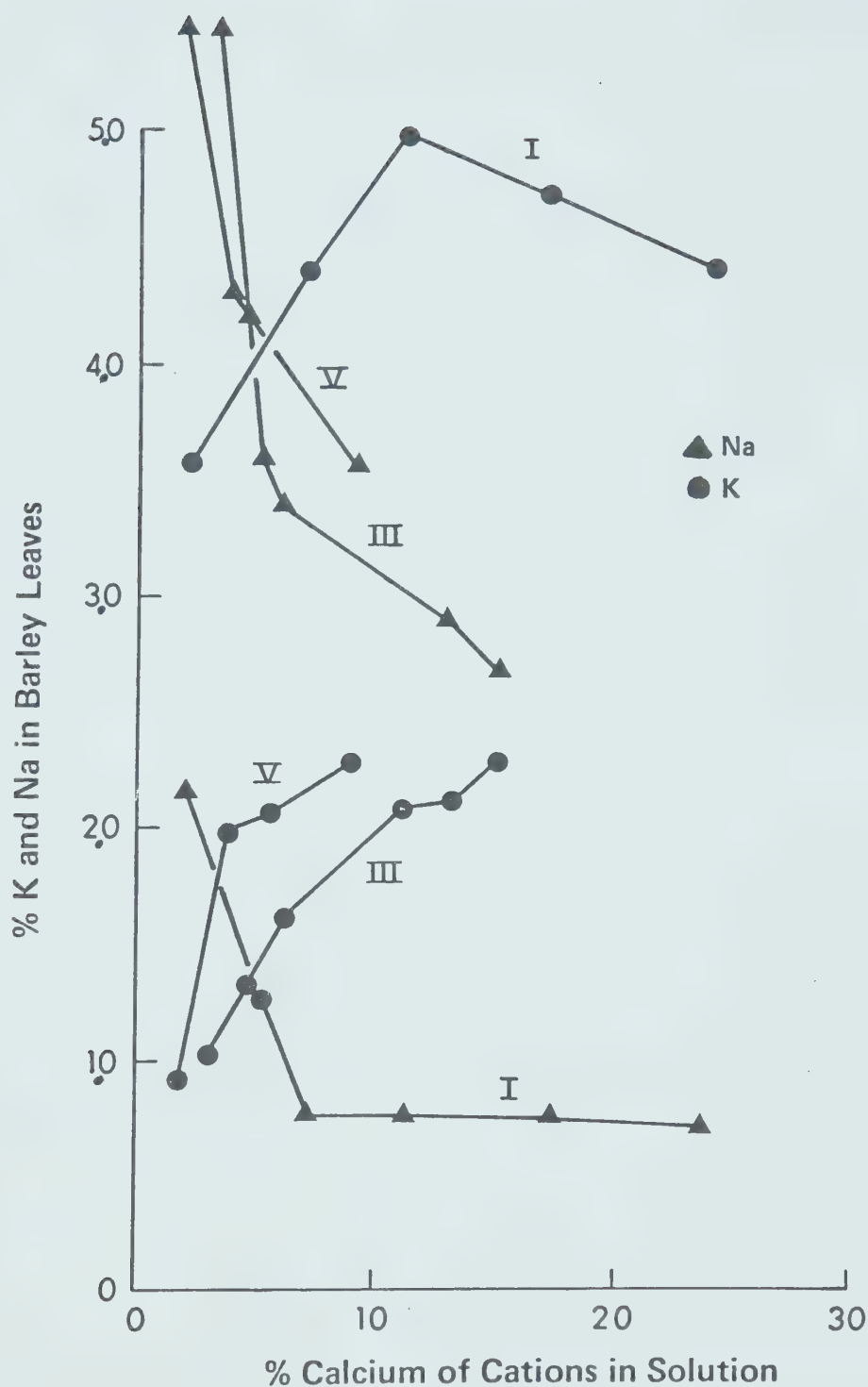


Figure 8. Uptake of potassium and sodium at different levels of calcium in solution from experiments I, III and V

by Epstein (1969 and 1972), in that, the mechanism which causes the absorption of potassium at low concentrations ($< 1.0 \text{ meqK/l}$) has a greater affinity for potassium than sodium. Long term field experiments on Solonetzic soils have shown that decreases in soil sodium and increases in soil calcium, by use of various ammendments were correlated with increased potassium levels in the crop. In some cases the potassium level in the leaves had increased from deficiency levels to sufficiency levels (Cairns et al. 1967; Cairns 1971). Therefore, the principles behind calcium involvement in sodium and potassium uptake may be important factors in assessing nutritional limitations on Solonetzic soils.

In conclusion, the dynamics of potassium and sodium selectivity and uptake along with yield of barley are conditioned by the proportions of calcium in the soil solution. Furthermore, calcium uptake is dependent on the ratio of calcium to total cations rather than the actual concentration of calcium per se.

SOIL STUDIES

I - MATERIALS AND METHODS

The first series of soil experiments were conducted to determine if barley grown in Solonchic soils, would have similar cation ratios in the foliage, after four weeks of growth, as that found in culture solutions simulating the displaced soil solution (at half available moisture) of Solonchic soils (Tables 5 and 6). To this end, barley (Hordeum vulgare var Galt) was grown in plastic pots (18cm x 17cm depth) which held between 2000 - 3000 grams of soil (air dry basis). The soil was first moistened to the half available moisture level using an atomiser. Reagent grade NH_4NO_3 and KH_2PO_4 were dissolved in the water, to add 35ppm, 9ppm and 22ppm of N, P and K respectively, to each pot, so that over the short growth period the macro-nutrients would not be limiting. The pots were covered with plastic film to prevent evaporation. After germination, the seedlings were thinned to give six uniform plants per pot. Perlite was added to the soil surface and the plastic film, with holes for each plant, placed over the top of each pot. During the four week growth period, distilled water was added as needed to maintain each pot at the half available moisture weight. However, due to the short growth period, and

large amount of soil little water was added. The moisture content of each soil fluctuated between -15 bar (or lower) and half available moisture. Under this range the Mg/Ca ratio and Ca/TC ratio does not vary drastically. For example, a saline Hemaruka Bnt horizon only showed a change of 3.62 to 3.50 in the Mg/Ca ratio from -15 bar to half available moisture percentage, while no change occurred with the Ca/TC ratio (Tables 5 and 7).

The second series of experiments were designed to determine the effect of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) ammendments, mixed into the soil, on the yield of barley and assess any changes in the cation ratios of the leaves. Only two soils were used, a Killam Bnt and a Duagh Ap (Chipman). Gypsum was mixed dry at the rate of 4.66 and 9.32 meq/100g with air dry Killam Bnt horizon samples to give the equivalent of approximately 9 and 18 tonnes of gypsum per hectare - 15cm depth. The Duagh Ap horizon from Chipman had only the high rate of gypsum mixed into the soil. Similar procedures were used as in the first experiment except the following: smaller pots were used (ID 15cm x 11cm depth); weight of soil was 2656 grams and 1550 grams of air dry soil in the case of the Killam Bnt and Duagh Ap respectively. All analyses of plant material were done by procedures outlined in other sections.

II - RESULTS AND DISCUSSION

1. Characteristics of barley growth on Solonetzic soil horizons

Data given in Table 23 show that similar growth performance was found from soil solutions in situ to that simulated in nutrient solution. Those soil horizons with adverse Mg/Ca ratios or Ca/TC ratios (e.g. Killam Bnt, Hemaruka Bnt and Duagh Ap) soon developed calcium deficiency symptoms and reductions in growth. Soil horizons with extremely high Mg/Ca ratios (i.e Killam and Hemaruka Bnt) developed severe calcium deficiency. In regards to the Duagh Ap, only one plant showed calcium deficiency symptoms, but all exhibited poor growth. This would indicate that growth performance can be estimated by displaced soil solutions.

Ratios of Mg/Ca and Ca/TC in the leaves were determined and the respective soil solution ratios were calculated (see Table 23) using the linear regression equations determined in solution culture (Figs. 6 and 7). Comparisons between the actual ratios in displaced solution (Tables 5 and 6) and the calculated ratios for the soil solution in situ (Table 23) show good agreement. Therefore, although the concentration of ions in leaves of plants grown in soil can differ to those grown in solution culture, due to variations in distribution of ions and water stress in the soil (Pitman

Table 23. Root growth and leaf content of barley grown in Solonetzic soil horizons

Soil	*** Root Growth	Calcium Deficiency	% in leaves				Mg/Ca			Ca/TC			
							Calculated +	Displaced ++	Colloids *	Calculated **	Displaced ++	Colloids *	
			Ca	Mg	Na	K							Mg/Ca
Killam Ap	+++	NO	0.42	0.36	0.83	3.68	0.86	1.35	0.69	0.46	0.22	0.26	0.23
Killam Bnt	+	YES	0.12	0.27	2.57	1.70	2.25	4.20	3.57	2.61	0.01	0.04	0.12
Duagh Ap	++	YES	0.17	0.26	2.90	1.28	1.53	2.70	1.42	1.00	0.03	0.07	0.15
Hemaruka Bnt	+	YES	0.16	0.28	2.90	1.31	1.75	3.20	3.57	0.93	0.02	0.07	0.33
Malmo Ap	+++	NO	0.55	0.40	0.45	4.29	0.73	1.10	0.92	0.39	0.34	0.37	0.45
Halliday Bt	++	NO	0.55	0.30	0.80	3.88	0.55	0.70	0.35	0.35	0.34	0.38	0.67

+ calculated from Fig. 6

++ average from Tables 5 and 6

* from Tables 2 and 3

** calculated from Fig. 7

*** Visual rating +++ vigorous; ++ moderate; + poor



7. Calcium deficiency in barley grown on a Killam Bnt horizon

1975)); the ratios of ions, especially calcium to other ions, does retain some correlation. This leads to the possibility, that the calcium status of the soil solution could be estimated by use of a biological assay such as leaf analysis. The relationship between ion uptake and ion concentrations in the soil solution would, of course, differ between plant species and age of plant. Therefore, the linear regression as given in Figs. 6 and 7 would only be specific for barley or perhaps the variety of barley used in this study.

Evidence that the soil solution alone characterizes

the environment of plant roots is difficult to determine from non-saline soil horizons (Table 23). Non-saline soils (i.e. Killam Ap, Malmo Ap and Halliday Bt) would maintain a similar Mg/Ca ratio in solution as on the colloids, especially as the selectivity of calcium and adsorption by clay is only preferred over magnesium by a factor of 1.2 (Bolt 1976). However, soils with appreciable salt content in the soil solution (i.e. Killam Bnt, Hemaruka Bnt and to a lesser extent Duagh Ap) would develop multiple equilibria between colloids, solid salts and ions in solution, at low moisture levels. This three phase system would ensure higher magnesium in the soil solution, at low moisture percentage, due to the greater solubility of magnesium sulphate over calcium sulphate (Khan and Webster 1966). The outcome of this would be a different Mg/Ca ratio in solution than on the colloids (Table 23). The calculation of the ratio in solution of calcium to other ions, using leaf analysis, in soils with appreciable salts in the soil solution, indicates that the soil solution (determined by displacement at half available moisture) characterizes the environment of plant roots. This is demonstrated by the agreement of the calculated Mg/Ca ratio and displaced Mg/Ca ratio, in contrast to the large difference between the calculated Mg/Ca ratio and the Mg/Ca ratio on the colloids (Table 23). Therefore, biological assessment of the calcium status of the soil solution

at field moisture levels, by use of leaf analysis, could be a useful assay of nutritional limitations in soils with saline soil solutions.

An interesting feature is that high magnesium in the soil solution of a Killam Bnt does not result in subsequent high magnesium uptake by the plant (Table 23). However, the adverse Mg/Ca ratio in solution is still reflected in the high Mg/Ca ratio in the plant as observed earlier (Fig. 6). Therefore, the importance of the Mg/Ca ratio is, again, demonstrated over that of magnesium uptake alone.

In all cases, high sodium uptake coincides with low potassium uptake, causing potassium to reach deficiency levels (0.70-1.50% dry weight). As the levels of potassium increase and sodium decrease a concomitant increase in calcium uptake occurs. Therefore, plant growth in the soil shows similar trends to that found in solution culture and indicates that ion uptake of sodium and potassium is modified by the calcium regime. Also, leaf analysis does provide an indirect assessment of the root environment.

Root growth was sensitive to the level of calcium to other ions (Table 18). Soils with adverse Mg/Ca ratios or very low Ca/TC ratios gave very poor root growth. This agrees with past work (Howard and Adams 1965; Tanaka and Woods 1972, 1973) which indicated that calcium deficiency is most severe in roots due to poor calcium mobility within

the plant and need for constant adequate calcium levels in solution.



8. Calcium deficiency in barley grown on a Hemaruka Bnt horizon

2. Effect of ammendments on plant growth

The effect of added gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) to supply soluble calcium to soils with low calcium to other cation ratios is given in Tables 24 and 25. In the case of the Killam Bnt horizon (Table 24) additions of calcium gave significant increases in yield over the check and prevented any occur-

Table 24. Growth and leaf content of barley grown on a Killam Bnt horizon amended with two rates of gypsum

	Yield (g)	Root ⁺ Growth	Calcium Defici- ency	% in leaves			Soil Solution	
				Ca	Mg	Na K	Mg/Ca ⁺⁺	Ca/TC*
Check	0.32 ^{**}	+	YES	0.15c	0.35a	2.31a 1.53b	4.30a	0.015b
9 tonnes Gypsum/ ha	0.55b	++	NO	0.16b	0.32b	1.76b 2.32a	3.70a	0.025a
18 tonnes Gypsum/ ha	0.81a	+++	NO	0.20a	0.32b	1.81b 2.29a	2.90b	0.050a

+ Visual rating +++ vigorous; ++ moderate; + poor

++ Calculated from Fig. 7

* Calculated from Fig. 8

** Values in the same column that have a letter in common are not significantly different ($P \leq 0.05$)

Table 25. Growth and leaf content of barley grown on a Duagh Ap (Chipman) horizon amended with gypsum

	Yield (g)	Root ⁺ Growth	Calcium Deficiency	% in leaves			Soil Solution	
				Ca	Mg	Na	Mg/Ca ⁺⁺	Ca/TC*
Check	0.82b ^{**}	++	One Plant	0.18b	0.27a	2.47a	2.70a	0.040b
18 tonnes Gypsum/ ha	1.42a	+++	NO	0.24a	0.25b	2.09a	1.70b	0.085a

+ Visual rating +++ vigorous; ++ moderate

++ Calculated from Fig.7

* Calculated from Fig.8

** Values in the same column that have a letter in common are not significantly different ($P \leq 0.05$)

rence of calcium deficiency. Root growth was also improved. This would indicate that soils with high Mg/Ca ratios or low Ca/TC ratios will respond to calcium ammendments as long as the ammendment is mixed well into the soil. The significant increase in yield from 9 tonnes/ha to 18 tonnes/ha of gypsum, indicates that even though calcium deficiency has been alleviated, a calcium limitation may still exist to prevent optimum yield.

Additions of calcium gave marked changes in the soil solution of the root environment. This caused significant changes in leaf composition (Table 24). Calcium was increased while magnesium decreased, resulting in changes in the Mg/Ca ratio. Use of the linear regression equations in Fig. 6 and 7, gave the estimated Mg/Ca ratios and Ca/TC ratios in the soil solution. Both ratios were significantly improved by the calcium ammendment, even though the Mg/Ca ratio still appeared limiting, even at the highest rate of gypsum. Therefore, additional rates of gypsum may give even greater yield increases. However, under natural conditions the magnesium exchanged by the calcium may be lost from the root environment due to leaching and allow a more favourable ratio of Mg/Ca to exist.

Comparison of the differential uptake of sodium and potassium, indicates that an improved calcium regime allows a significant increase in potassium uptake, followed by a concomitant decrease in sodium uptake. This occurs in the

absence of leaching when both soils contain the same amounts of sodium and potassium. In regard to the check, (Table 24) the low level of potassium in the leaves borders on the range commonly considered to indicate potassium deficiency (0.70-1.50% dry weight). Therefore, the addition of calcium not only ameliorates calcium deficiency but also prevents the possibility of potassium deficiency caused by impeded uptake due to sodium competition.

Similar trends were found when gypsum was added to a Duagh Ap (Chipman) horizon (Table 25). Although calcium deficiency was only observed on one plant (out of 18) in the check soil, the addition of calcium did significantly increase yield and give similar changes in leaf analysis, as found with the Killam Bnt amended soil. This would indicate that calcium limitations ("hidden hunger") exist in the Ap horizon of some Solonetz soils and prevent optimum yield being obtained.

In conclusion, the results from amending soils with calcium agree with that found in solution culture. They also illustrate the usefulness of displaced soil solutions in predicting the calcium status of Solonetzic soils. Low Ca/TC ratios or high Mg/Ca ratios, as determined by displacement technique, in the soil solution were useful parameters for evaluating the need for calcium amendments.



9. Effect of added gypsum on barley growth on a Killam Bnt horizon



10. Effect of added gypsum on barley growth on a Duagh Ap (Chipman) horizon

SUMMARY AND CONCLUSIONS

Characterization of several Solonetzic soils gave results in agreement with earlier work (Bowser et al. 1962; Cairns 1961). Analysis of saturation paste extracts indicated that an increase in calcium and calcium to total cation ratio (Ca/TC) occurred with a concomitant decrease in sodium and magnesium to calcium ratio (Mg/Ca) along the Solonetz to Solod sequence. Although the soluble Mg/Ca ratio is lower in the Solod soils, the actual concentration of magnesium is sometimes increased over that found in the saturation paste extracts of Solonetz and Solodized Solonetz soils.

In regards to the exchangeable cations, an increase in the calcium to sodium ratio and decrease in the magnesium to calcium ratio occurs from a Solonetz to a Solod soil. The calcium to sodium imbalance in the Solonetz or Solodized Solonetz soil is demonstrated by the positive value given for the gypsum requirement test, as compared to the Solod soil which had no gypsum requirement. Levels of exchangeable magnesium showed no consistent trends between Solonetz and Solod soils. Therefore, both soluble and exchangeable phases, in general, show an increase in calcium and decrease in sodium along the Solonetz to Solod

sequence, as the main chemical characteristic. Exchangeable sodium percentages are below 25 in the Bnt horizons of Solonetz or Solodized Solonetz soils and would not constitute a nutritional problem for most grasses or legumes according to Bernstein (1975) and Pearson (1960). However, the relatively high exchangeable magnesium would develop nutritional problems when coupled with the low exchangeable calcium found in the Solonetz Ap or Bnt horizons of both the Solonetz and the Solodized Solonetz soils studied (Joffe and Zimmerman 1944).

Miscible displacement of the soil solution at the moisture level between -15 bar and -1/3 bar, using either calcium chloride or ethanol, gave similar and consistent analytical results for ionic constituents of consecutive portions of the displaced solution. Differences between soil solutions of Solonetz or Solodized Solonetz and Solod soils, at field moisture levels, were similar to those explained above. Comparison of saturation paste extracts and displaced soil solutions showed an expected increase in salinity as the moisture level in the soil decreased. This is an important factor, as the linear increase in salinity is specific for each soil, therefore concentrations of ions cannot be extrapolated from saturation paste extracts alone. Magnesium to calcium ratios were similar in the soil solution at field moisture levels as at satur-

ation paste. However, highly saline soil solutions (e.g. Hemaruka Bnt) gave higher Mg/Ca ratios at field moisture levels than at saturation paste due to the relatively greater solubility of magnesium sulphate over calcium sulphate. In general, the Ca/TC ratio is increased at the field moisture levels over that found at saturation paste. This was considered due to the dilution and valency effect, whereby the concentrating of a soil solution system causes adsorption of lower valency ions (i.e. sodium) over that of higher valency ions (i.e. calcium and magnesium). Therefore, with the exception of relatively saline soil solutions, saturation paste extracts are adequate for estimating ratios of calcium to other ions at field moisture levels. The results from saturation paste extracts, exchangeable cations and displaced soil solutions, indicate that physiological factors such as high salinity and specific salt effects caused by unbalanced ratios of calcium to other ions, are present in the Ap horizon of Solonetz and Bnt horizon of Solonetz and Solodized Solonetz soils studied.

Solution culture studies simulating the concentrations and ratios of ions found in the field moisture range, allowed the effect of physiological factors to be assessed free of any soil physical effects. Increasing Mg/Ca ratios over 1.0 gave a decrease in growth of barley tops and roots,

regardless of the salinity level of the solution. Similar results were observed when the Ca/TC ratio fell below 0.15. The Mg/Ca ratio was considered part of the Ca/TC ratio, as the latter ratio reflected the total cation environment including magnesium. Therefore, the Ca/TC ratio was more versatile. However, the Mg/Ca ratio was still a useful parameter for high magnesium soil solutions. In general, the effect of the adverse ratios was more pronounced at the seedling stage. Adverse ratios produced yield declines which were followed by evidence of plant stress diagnosed as calcium deficiency. Typical symptoms were withering of the emerging third or fourth leaf and spiralling of the leaf base. Symptoms were more pronounced under adverse magnesium to calcium ratios. Yield decline and calcium deficiency symptoms were not correlated with actual concentrations of magnesium or calcium in solution but were with the ratio of calcium to other ions. It is considered that the uptake of calcium is disrupted or interfered with by other ions, so that, the calcium deficiency symptoms are evidence of ion antagonistic effects on calcium uptake. This could be overcome by increasing calcium levels to give optimum ratios of calcium to other ions. Therefore, the physiological role of calcium in ameliorating the detrimental effects of other ions on plant growth is an important factor for consideration on solonchic soils. Further-

more, high correlation coefficients between yields and Mg/Ca ratios and Ca/TC ratios provide useful parameters to assess possible nutritional limitations, regardless of salinity, for Solonetzic soils.

The well known salinity limitation for plant growth on Solonetzic soils was further demonstrated by displaced soil solutions. Electrical conductivity values for Bnt horizons of Solonetz and Solodized Solonetz soils, displaced at half available moisture percentage, ranged from 6.0 - 15.0 mmhos/cm. This indicates the potential salinity stress for plant growth present in sub-surface horizons of the above Solonetzic soils.

Leaf and root analyses of barley grown in solution culture showed that the percent calcium content was correlated with the Ca/TC ratio in solution ($r = 0.931$). Low Ca/TC ratios in solution gave low calcium in the plant. This occurred even when high amounts of calcium were used, so that, high calcium (15meq/l) and low Ca/TC ratio (0.11) would give decreased yield and low levels of calcium in the leaf (0.22% dry weight) to cause calcium deficiency symptoms. Therefore, the amount of calcium required in solution for optimum plant growth depends on the amount of other ions in solution. Furthermore, the ratio of calcium to other ions is shown to be important not only at the two extremes of nutrient supply, namely toxicity and deficiency,

but at any level of calcium. The ratio of Mg/Ca in solution was also correlated with the percent Mg/Ca in the leaves of barley ($r = 0.979$). Sodium and potassium uptake as reflected by their percent dry weight in the leaves was determined by the Ca/TC ratio in solution. As the Ca/TC ratio in solution decreases, sodium uptake increases at the expense of potassium uptake. This occurs regardless of the concentrations of sodium and potassium in solution. It was found that a Ca/TC ratio of greater than 10 percent was needed in solution, to maintain adequate potassium levels in the plant, so that potassium would not approach a deficiency range.

Growth of barley on Ap or Bnt horizons of Solonchic soils confirmed the results found in solution culture. Soil horizons with adverse Mg/Ca ratios or Ca/TC ratios, as determined by analysis of the displaced soil solution, gave evidence of calcium deficiency and reduced growth. Furthermore, the dynamics of sodium and potassium uptake, along with the modifying effect of calcium were observed in soil grown plants and were similar to that reported for solution culture. Use of a regression equation to determine the Mg/Ca ratio in solution from the Mg/Ca ratio in the leaves, showed that solutions displaced from saline soils adequately characterized the root environment. Applications of calcium amendments (i.e. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) im-

proved growth of barley and prevented calcium deficiency, on those soils with adverse ratios of calcium to other ions, as well as improving potassium uptake. Therefore, similar growth of barley found on soil horizons and in displaced soil solutions, indicate that the latter is a good estimate of the in situ soil solution.

In conclusion, then, the Ap horizon of the solonetz and Bnt horizon of the Solonetz and Solodized solonetz soils studied had an adverse ratio of calcium to other ions, in the soil solution, to give calcium limitations for optimum plant growth. The problem is not low calcium per se but low calcium and high levels of other ions which allow conditions conducive for salinity induced calcium deficiency. This has an important application for root growth, especially on Solodized Solonetz soils where a favourable A horizon and inhospitable B horizon would affect root penetration and distribution, as well as moisture and nutrient availability. Certainly, levels of calcium in the B horizon may have a major effect on plant growth, due to the effect on root development, regardless if the calcium level in the A or C horizon is adequate.

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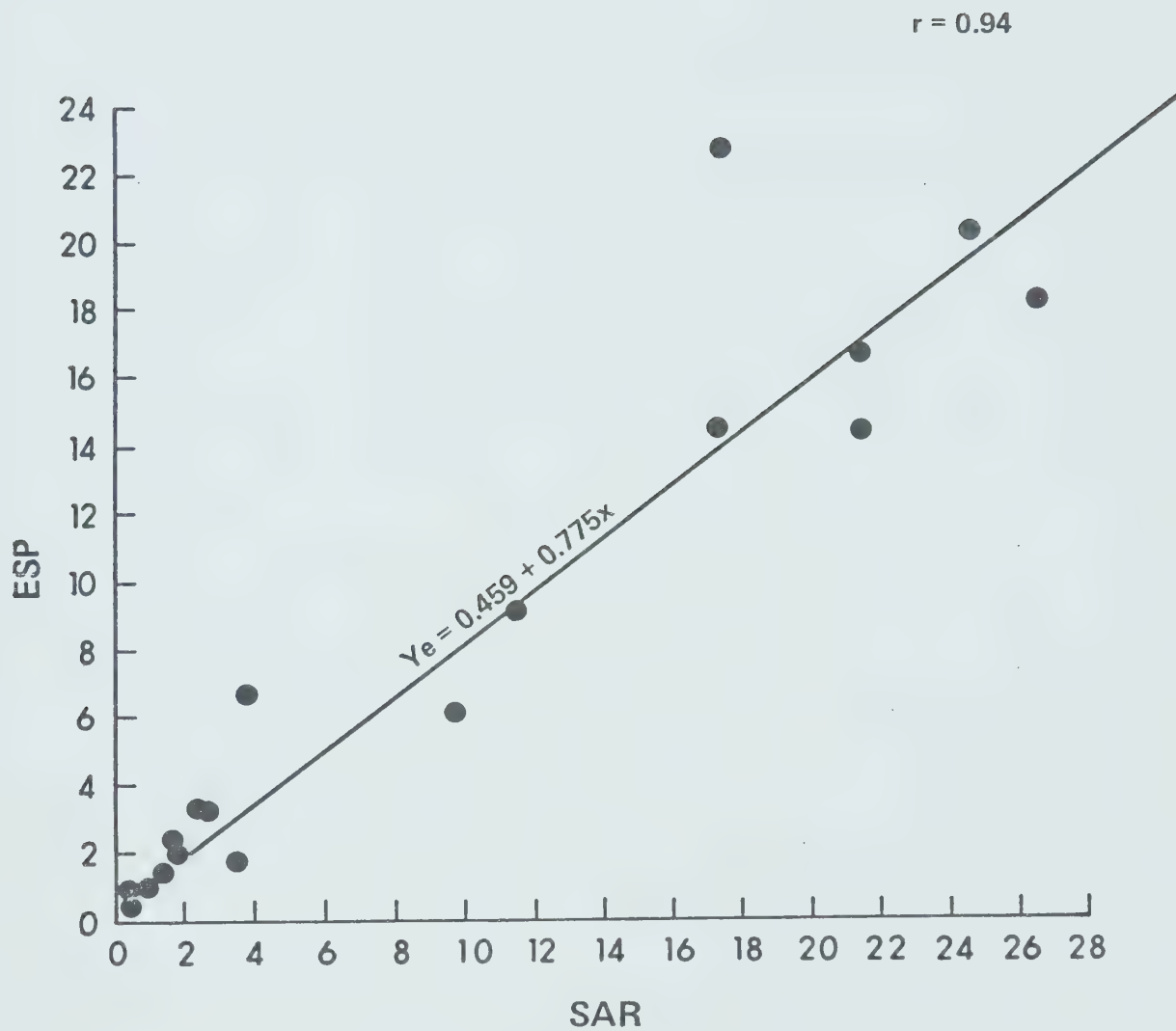
APPENDICES

APPENDIX I

Characterization of Moisture Percentages of Soils under Study

Soil	Horizon	Air dry	15bar	$\frac{1/3+15\text{bar}}{2}$	1/3bar	Saturation Paste
Duagh	Ap	5.9	27.8	35.1	42.4	73.5
	Bnt	6.0	24.0	31.0	38.1	79.5
Malmo	Ap	9.7	26.9	36.5	46.1	80.0
	Bt	5.8	15.8	22.4	29.1	50.8
Killam	Ap	5.0	15.5	22.8	30.1	67.1
	Bnt	4.6	17.5	25.5	33.6	58.6
Daysland	Ap	4.5	17.3	25.6	33.9	65.7
	Bnt	4.5	12.3	17.5	22.8	47.2
Hemaruka	Ap	2.8	12.2	18.0	23.8	53.2
	Bnt	3.6	21.1	25.5	30.0	43.5
Halliday	Ap	3.8	10.6	15.8	21.0	53.5
	Bt	5.8	14.9	20.2	25.5	48.3

Appendix II



Comparison between ESP and SAR (Saturation extract)

APPENDIX III

Nutrient Solution (Hoagland and Snyder 1933)

	meq/l of Nutrient Solution
KNO_3	5
$\text{Ca}(\text{NO}_3)_2$	10
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	4
KH_2PO_4	1

APPENDIX IV

Micronutrient supplement (Hewitt and Smith 1975)

	meq/l of Nutrient Solution	g/l for Stock Solution ⁺
$\text{MnSO}_4 \cdot 4\text{H}_2\text{O}$	0.02	2.23
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	0.002	0.29
H_3BO_3	0.15	3.10
$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	0.001	0.12
NaCl	0.1	5.85
$\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$	0.0004	0.053
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	0.002	0.25

⁺ 1 ml of stock solution required for each 1000 ml of nutrient solution

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